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FIRESTORM ANALYSIS

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FIRESTORM ANALYSIS

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T. E. Lommasson
J. A. Keller
R. G. Kirkpatrick

Prepared on Contract No. 13-248

for

Division of Fire Research
U. S. Forest Service
Department of Agriculture
Washington, D. C.

This Project Sponsored By
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February 1, 1967

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by

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FIRESTORM ANALYSIS

1.0 INTRODUCTION

1.1 Objectives

The following general objectives were specified for this study:

a) Compute the radial inrush wind (v_w) associated with a mass fire as a function of time and various fuel bed parameters,

b) Investigate the sensitivity of v_w to variations in certain of the fuel bed parameters, and

c) Conduct an analytical study of the case in which fire spread is accelerated by wind and/or flame interaction until coalescence.

1.2 Background

The basic point of departure for this research was Ref. 1, in which a hypothesis was developed relating radial inrush wind velocity at the edge of a potential firestorm area to the energy release rate of fires within the area and to the size of the area itself. The value of the constant in the equation relating these parameters was determined by "fitting" an equation derived from physical considerations to estimated "worst case" conditions during the Hamburg firestorm. One degree of freedom in the "constant" term allowed this fit to be made.

In Appendix IB, the equation of Ref. 1 is expanded to express the energy release rate of the fires in terms of the following parameters:

n	the number of initial fires,
FL	the fuel loading,
E_{fuel}	the energy content of the fuel,
A_{SV}	the area of a single fire which is in the violent burning stage* at a given time,
A_{SR}	the area of a single fire which is in the residual burning stage* at a given time,
$E_{frac, viol}$	the fraction of E_{fuel} released during the violent burning stage*,
$E_{frac, resid}$	the fraction of E_{fuel} released during the residual burning stage*,
Δt_V	the duration of the violent burning period,* and
Δt_R	the duration of the residual burning period*.

In Appendices IA and IC, equations are derived which, for certain assumptions, represent A_{SV} and A_{SR} as a function of time, spread rate, and other parameters for three different spread conditions.

1.3 Method of Calculation

A computer program to calculate v_w was written based upon Eq. (IA-1) and Tables IA-I and IA-II. The input values used are listed in Section IA.4. The results of these calculations are presented graphically in

---

* The definitions of "violent" and "residual" burning regimes are based upon Ref. 2.

Appendix IV. A second part of the program calculates the partial derivative of v_w with respect to seven selected parameters based upon the rationale of Appendix II and using the inputs listed in Table II-I. The results of this series of calculations is presented in Appendix V. A listing of this program, its input requirements, and a sample output page from each part are contained in Appendix III.

The accelerated spread study considers that radial spread is accelerated by interaction effects (after adjacent fires reach a certain minimum separation distance). Four initial spread modes are investigated: a constant rate of radial increase, a constant rate of area increase, and two logarithmic rates of radial spread.*

The computer program listed in Appendix VII calculates spread rate, fire radius, and distance to the point at which flame fronts merge as a function of time for each initial spread mode. This program is based upon the equations of Appendix VI. Appendix VIII contains eight graphs showing radial spread rate as a function of time and of fire radius for each of the initial spread modes, with the point at which acceleration begins indicated on each curve.

1.4 Limitations

Inherent in the rationales and the results of this study are, of course, the approximations and assumptions made in deriving the heuristic model

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* Provided by Mr. C. C. Chandler, Division of Fire Research, U. S. Forest Service, Washington, D. C.

from Ref. 1 and the modifications to it described in Section 1.2. In particular, the "worst case" conditions in Hamburg, from which the value of the constant was obtained, corresponds to 100% simultaneous involvement of all structures in an urban area during the violent burning period of the initial fires. This study considers a continuous wildland fuel bed with somewhat different burning characteristics. The degree of correspondence between these two cases is not, as yet, firmly established.

All of the v_w computations are made using average values for the rate of energy release term, as reflected by the parameters listed on pages IA-1 and IA-2.

Also, the type and rate of fire spread which occur in a fuel bed of the sort considered here will probably require considerable further investigation before the functional dependencies and appropriate parameter values are clearly defined. The preliminary work on accelerated spread in this study is one course of investigation that may yield a better understanding of these relationships.

The spread rate relations assumed are approximations, and in the real world probably represent rough average values as they develop as a function of time.

This entire study may be viewed as a project that has generated a number of rough hypotheses which may now be tested and assessed as to validity and utility.

2.0 RESULTS

2.1 Radial Inrush Wind Velocity Curves

The 45 families of curves in Appendix IV represent v_w as a function of n for ten values of time after ignition. A family of curves was constructed for each combination of values of 3 spread cases, 3 fuel loadings, and 5 area sizes. Each family is bounded above by the coalescence locus, as discussed in Appendix ID.

In general, an increase in the number of initial ignitions decreases the time at which the maximum value of v_w ($\hat{v}_w$) occurs, as would be expected. For Case 1 (constant area increase), $\hat{v}_w$ (as described by the coalescence locus) increases considerably as a function of n. On the other hand, for Case 2 (constant rate of perimeter or radial increase), the coalescence locus is much "flatter"; i.e., $\hat{v}_w$ is fairly constant with respect to n. This simply means that, as n increases, the time to coalescence is less for spread Case 1 than for spread Case 2, all other factors being equivalent. Also, for the values of the spread constants considered in this analysis, $\hat{v}_w$ appears to occur at a much earlier time for Case 1 than for Case 2, which is intuitively expected.

2.2 Sensitivity Analysis

Appendix V contains seven families of curves which represent $\frac{\partial v_w}{\partial \mu_i}$ at ten times after ignition as a function of μ_i with the other parameters μ_j ($j \neq i$) held at their "representative values." These curves are drawn

from the output of Part II of the computer program listed in Appendix III. This part of the program and its inputs are based upon the rationale described in Appendix II.

The partial derivative $\frac{\partial v_w}{\partial \mu_i}$ indicates the rate of change of v_w with respect to μ_i. The sign of $\frac{\partial v_w}{\partial \mu_i}$ indicates the direction of change, e.g., if $\frac{\partial v_w}{\partial \mu_i} > 0$, an increase in the value of μ_i will result in an increase in the value of v_w. Conversely, if $\frac{\partial v_w}{\partial \mu_i} < 0$, then an increase in μ_i will yield a decrease in v_w. The magnitude $\left| \frac{\partial v_w}{\partial \mu_i} \right|$ serves as an index of the rate of change for various points on the family of curves associated with a particular μ_i. Table 2.2-I lists the sign of $\frac{\partial v_w}{\partial \mu_i}$ and the behavior of $\left| \frac{\partial v_w}{\partial \mu_i} \right|$ for the seven parameters considered.

2.3 Accelerated Spread Study

Appendix VI considers the case in which radial spread rate is accelerated by interaction effects when adjacent fires are sufficiently close. This case is investigated for four initial spread modes; two logarithmic rates of radial increase,* the constant rate of radial spread (M = 0.01 ft/sec) used for Case 2b of the v_w calculations, and the constant rate of area spread (K_1 = 5.0 ft^2/sec) used for Case 1 of the v_w calculations.

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* Provided by Mr. C. C. Chandler, Division of Fire Research, U. S. Forest Service, Washington, D. C.

TABLE 2.2-I

Sensitivity Summary

Parameter	Sign of $\frac{\partial v_w}{\partial \mu_i}$	Change in $\left\lvert \frac{\partial v_w}{\partial \mu_i} \right\rvert$ with increasing μ's for a fixed time.	Change in $\left\lvert \frac{\partial v_w}{\partial \mu_i} \right\rvert$ with increasing time for a fixed value of μ_i.
$\mu_1 = n$	+	decreasing	increasing
$\mu_2 = A$	-	decreasing	increasing
$\mu_3 = FL$	+	decreasing	increasing
$\mu_4 = EF$	+	decreasing	increasing
$\mu_5 = E_{frac, viol}$	+	decreasing	increasing for $t \leq 32$ min. decreasing for $t > 32$ min.
$\mu_6 = E_{frac, resid}$	-	increasing	increasing for $t \leq 32$ min. decreasing for $t > 32$ min.
$\mu_7 = r$ $(r = 2\pi M^2 t)$	+	decreasing	decreasing

Equations are developed for radial spread rate, fire radius, and distance to merging as a function of time for each initial spread mode. The computer program listed in Appendix VII is based upon these equations.

The eight graphs in Appendix VIII represent radial spread rate as a function of time and of fire radius for each initial spread mode.

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1. Lommasson, T. E., Preliminary Investigation of Firestorm Start-Criteria, The Dikewood Corporation DC-TN-1050-1, Contract OCD-PS-65-53, Albuquerque, New Mexico, June 15, 1965.

2. Chandler, C. C., Storey, T. G., and Tangren, C. D., Prediction of Fire Spread Following Nuclear Explosions, U. S. Forest Service Research Paper PSW-5, Contract OCD-OS-62-131, Berkeley, California, 1963.

APPENDIX IA

RATIONALE FOR COMPUTATION OF RADIAL INRUSH WIND VELOCITY

IA.1 Basic Equation and Parameter Definitions

The basic equation* is

$$v_w = \left(\frac{88}{1000}\right)\left(\frac{50}{1089}\right)^{1/3} \cdot \frac{[(n)(FL)(E_{fuel})]^{1/3}}{A^{1/6}} \cdot \left[\frac{A_{SV}(r,t,\Delta t_V)\cdot E_{frac,\,viol}}{\Delta t_V} + \frac{A_{SR}(r,t,\Delta t_V,\Delta t_R)\cdot E_{frac,\,resid}}{\Delta t_R}\right]^{1/3} \quad \text{(IA.1)}$$

Where

v_w	is the radial inrush wind velocity at the periphery of a circular area A within which fires are burning, in miles per hour
n	is the number of initial fires. [$n = n_d \cdot (A)$, where n_d is the number of initial fires per square mile]
FL	is the fuel loading, in tons per acre
E_{fuel}	is the caloric content of the fuel in Btu/lb
A	is the total area within which fires are started, in square miles
A_{SV}	is the area which is in the violent burning regime at time t, in square feet

* This equation is based on work done in Ref. 1. A derivation of the form used in this study from those in Ref. 1 is given in Appendix IB.

r is the spread rate; if A_S denotes the total area, in square feet, over which the fire has spread at time t,

$$r = \frac{dA_S}{dt} \qquad \text{(IA. 2)}$$

t is the time after ignition, in seconds

Δt_V is the duration of the violent burning period, in seconds

$E_{frac, viol}$ is the fraction of the total available energy of the fuel which is released during the violent burning period

A_{SR} is the area which is in the residual burning regime at time t, in square feet

Δt_R is the duration of the residual burning period, in seconds

$E_{frac, resid}$ is the fraction of the total available energy of the fuel which is released during the residual burning regime

IA. 2 Assumptions

A. All fires have negligible initial areas; i. e., they are effectively "point fires".

B. Fire spread starts immediately after initiation of any given "point fire", and each fire spreads in the same manner at the same rate symmetrically around the "point fire" until coalescence.

C. All fires are started simultaneously from a uniform distribution of ignitions and burn in identical fuel beds.

D. Three rates of area spread with time will be considered:

1) $\frac{dA_S}{dt} = r_1 = K_1$, which represents a constant rate of area growth,

2) $\frac{dA_S}{dt} = r_2 = Bt$, which represents a constant rate of perimeter increase,

3) $\frac{dA_S}{dt} = r_3 = Ct$, which represents a constant rate of radial spread.

The expressions for B and C are derived in Appendix IC.

IA. 3 Procedure

At any time t, the area into which a given fire has spread, A_S, is composed, ideally, of three regions:

1) The violently burning part, A_{SV},

2) The residually burning part, A_{SR}, and

3) The burned-out portion, A_{SBO}, so that

$$A_S(t) = A_{SV}(t) + A_{SR}(t) + A_{SBO}(t) \qquad \text{(IA. 3)}$$

From the definitions, it is apparent that

$$A_{SV}(t) = A_S(t) - A_S(t - \Delta t_V)$$

$$A_{SR}(t) = A_S(t - \Delta t_V) - A_S[t - (\Delta t_V + \Delta t_R)]$$

$$A_{SBO}(t) = A_S[t - (\Delta t_V + \Delta t_R)] \qquad \text{(IA. 4)}$$

Taking r(t) as the spread rate, one may write the following relations:

$$A_{SBO} = \begin{cases} 0 \text{ if } t \leq \Delta t_V + \Delta t_R \\ \displaystyle\int_{\Delta t_V + \Delta t_R}^{t} r[t - (\Delta t_V + \Delta t_R)]\, dt \text{ for } t > \Delta t_V + \Delta t_R \end{cases} \quad \text{(IA. 5)}$$

$$A_{SR} = \begin{cases} 0 \text{ if } t \leq \Delta t_V \\ \displaystyle\int_{\Delta t_V}^{t} r(t - \Delta t_V)\, dt - A_{SBO} \text{ for } t > \Delta t_V \end{cases} \quad \text{(IA. 6)}$$

and

$$A_{SV} = \int_0^t r(t)\, dt - A_{SR} - A_{SBO} \quad \text{(IA. 7)}$$

These expressions have been evaluated and the results are given in Tables IA-I and IA-II, which present formulae for A_{SV}, A_{SR}, and A_{SBO} as a function of time for the two basic spread modes given in paragraph IA. 2D above.

Case 1. Constant area increase.

$$r = \frac{dA_S}{dt} = K_1 \text{ ft}^2 / \text{sec} \quad \text{(IA. 8)}$$

Table IA - I

A_S \ t	$0 \leq t \leq \Delta t_V$	$\Delta t_V < t \leq \Delta t_V + \Delta t_R$	$t > \Delta t_V + \Delta t_R$
A_{SV}	rt	$r \cdot \Delta t_V$	$r \cdot \Delta t_V$
A_{SR}	-0-	$r \cdot (t - \Delta t_V)$	$r \cdot \Delta t_R$
A_{SBO}	-0-	-0-	$r \cdot [t - (\Delta t_V + \Delta t_R)]$

In this case

$$n_c = \frac{A}{K_1 t} \times (5280)^2 \qquad \text{(IA. 9)}$$

where n_c is the number of initial fires necessary to achieve coalescence in area A by time t.*

Case 2. $$r = \frac{dA_s}{dt} = K_2 t \qquad \text{(IA. 10)}$$

(2a) $K_2 = B$ (constant rate of perimeter increase) $B = L^2/(2\pi)$ where L is rate of change of perimeter, in feet per second.**

(2b) $K_2 = C$ (constant rate of radial increase) $C = 2\pi M^2$ where M is rate of change of radius, in feet per second.**

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* The derivation of the coalescence relations is given in Appendix ID.

** The derivation of these relationships is given in Appendix IC.

Table IA - II

A_S \ t	$0 \le t \le \Delta t_V$	$\Delta t_V < t \le \Delta t_V + \Delta t_R$	$t > \Delta t_V + \Delta t_R$
A_{SV}	$\frac{rt}{2}$	$\frac{r}{2} \cdot \left[2\Delta t_V - \frac{(\Delta t_V)^2}{t} \right]$	$\frac{r}{2} \cdot \left[2\Delta t_V - \frac{(\Delta t_V)^2}{t} \right]$
A_{SR}	-0-	$\frac{r}{2} \cdot \left[t - 2\Delta t_V + \frac{(\Delta t_V)^2}{t} \right]$	$\frac{r}{2} \cdot \left[2\Delta t_R - \frac{2\Delta t_V \Delta t_R}{t} - \frac{(\Delta t_R)^2}{t} \right]$
A_{SBO}	-0-	-0-	$\frac{r}{2} \cdot \left[t - 2(\Delta t_V + \Delta t_R) + \frac{(\Delta t_V + \Delta t_R)^2}{t} \right]$

and

$$n_c = \frac{2A}{K_2 t^2} \times (5280)^2 \qquad \text{(IA. 11)}$$

IA. 4 Input Parameter Values

Calculations of v_w and n_c have been made for each case, using each combination of the parameter values:

n_d = 2000, 3000, 4000, 4500, 5000, 6000, 7000, 10,000

A = 1.0, 5.0, 10.0, 15.0, 25.0 mi^2

FL = 5, 15.0, 30.0 tons/acre

E_{fuel} = 7000 Btu/lb

Δt_V = 360 sec

Δt_R = 4200 sec

K_1 = 5.0 ft^2/sec

M = .01 ft/sec

L = .1 ft/sec

$E_{frac, viol}$ = 0.4

$E_{frac, resid}$ = 0.6

t = 2, 4, 6, 8, 16, 24, 32, 48, 64, 80 minutes

Note that the total number of fires burning in a given area is represented by $n = n_d \cdot A$.

IA. 5 Method of Calculation

A computer program was written based upon the above equations. Using the inputs listed above, it calculates v_w as a function of time and n for each combination of the other parameters. A listing of this program, its input format requirements, and a sample output page is included in Appendix III. The output is grouped so that:

1) All pages pertaining to a given spread rate are together.
2) Within a given case, all pages with a specific FL are together.
3) Each page of the output has all the points for a specific area size, given the case and FL.

The results of these calculations are presented graphically in Appendix IV.

APPENDIX IB

DERIVATION OF THE BASIC EQUATION

Equation (29) of Ref. 1 gives

$$v_w = \frac{(88 \times 10^{-3}) \left[\sum_{i=1}^{n} \frac{dE_{T(i)}}{dt} \right]^{1/3}}{\sqrt[6]{A}} \qquad \text{(IB. 1)}$$

where v_w is the radial inrush wind velocity at the periphery of area A, in miles per hour, n is the number of initial fires started in an area A, and $\frac{dE_{T(i)}}{dt}$ is the energy release rate for a single fire, in Btu/sec at time t. Assuming identical simultaneously ignited fires in a continuous fuel bed with uniform characteristics, the total amount of energy released during the violent burning period is given by the product of:

1) the total number of fires,

2) the fuel loading (lbs/ft^2),

3) the caloric content of the available fuel (Btu/lb),

4) the area (ft^2) which is burning violently at the time in question, and

5) the fraction of the total energy of the fuel which is released during the violent burning period.

The average energy release rate during the violent burning regime is the total energy released during that time divided by the length of the violent burning period, in seconds. Symbolically,

$$\left[\sum_{i=1}^{n} \frac{dE_{T(i)}}{dt}\right]_{viol} = \frac{(n)(FL)(E_{fuel})(A_{SV})(E_{frac,\,viol})}{\Delta t_V} \qquad \text{(IB. 2)}$$

Similarly, the energy release rate during the residual burning period may be represented by

$$\left[\sum_{i=1}^{n} \frac{dE_{T(i)}}{dt}\right]_{resid} = \frac{(n)(FL)(E_{fuel})(A_{SR})(E_{frac,\,resid})}{\Delta t_R} \qquad \text{(IB. 3)}$$

If fuel loading (FL) is expressed in tons per acre, the expressions on the right in Eqs. (IB. 2) and (IB. 3) must be multiplied by the conversion factor (50/1089).

The total energy release rate is the sum of the release rate for those portions of the fuel bed in the violent burning regime and for the portions in the residual regime, or

$$\left[\sum_{i=1}^{n} \frac{dE_{T(i)}}{dt}\right]_{total} = \left[\sum_{i=1}^{n} \frac{dE_{T(i)}}{dt}\right]_{viol} + \left[\sum_{i=1}^{n} \frac{dE_{T(i)}}{dt}\right]_{resid} \qquad \text{(IB. 4)}$$

Substituting Eqs. (IB. 2), (IB. 3), and (IB. 4) into Eq. (IB. 1), using the conversion factor, and simplifying yields

$$v_w = \left(\frac{88}{1000}\right)\left(\frac{50}{1089}\right)^{1/3} \frac{\left|(n)(FL)(E_{fuel})\right|^{1/3}}{\sqrt[6]{A}} \left[\frac{A_{SV} \cdot E_{frac,\,viol}}{\Delta t_V} + \frac{A_{SR} \cdot E_{frac,\,resid}}{\Delta t_R}\right]^{1/3} \qquad \text{(IB. 5)}$$

which is the desired result. In this expression A_{SV} is a complex function of r, t, and Δt_V, and A_{SR} is a complex function of r, t, Δt_V and Δt_R

APPENDIX IC

DEVELOPMENT OF SPREAD RATE RELATIONSHIPS

The expressions for B and C, as defined under assumption (D), Section IA. 2, may be derived as follows:

a) Let the perimeter of a fire be approximated by $P = 2\pi r_c$, where r_c is the radius of the circular fire front and is a function of time. If the rate of perimeter growth is constant, then

$$\frac{dP}{dt} = L \quad , \tag{IC. 1}$$

where L is the constant rate of perimeter increase in units of length per unit of time.

From Eq. (IC. 1),

$$P = Lt = 2\pi r_c \quad , \tag{IC. 2}$$

and

$$r_c = \frac{Lt}{2\pi} \quad . \tag{IC. 3}$$

Now,

$$A_S = \pi r_c^2 = \frac{L^2 t^2}{4\pi} \quad . \tag{IC. 4}$$

Differentiation of Eq. (IC. 4) yields

$$\frac{dA_S}{dt} = \frac{L^2 t}{2\pi} = r_2 = Bt \quad . \tag{IC. 5}$$

Solving for B yields

$$B = \frac{L^2}{2\pi} \quad . \tag{IC. 6}$$

b) Similarly, if r_c again represents the radius of a circular fire front and M represents a constant rate of radial spread in units of length per unit of time, one may write

$$\frac{dr_c}{dt} = M \quad , \tag{IC. 7}$$

so that

$$r_c = Mt \quad , \tag{IC. 8}$$

and

$$A_S = \pi r_c^2 = \pi M^2 t^2 \quad . \tag{IC. 9}$$

Hence

$$\frac{dA_S}{dt} = 2\pi M^2 t = r_3 = Ct \quad , \tag{IC. 10}$$

and therefore

$$C = 2\pi M^2 \quad . \tag{IC. 11}$$

APPENDIX ID

DERIVATION OF COALESCENCE EQUATIONS

The v_w versus n curves are bounded by the "coalescence locus", which may be defined as the number of initial fires necessary to achieve coalescence* by a specified time.

Assuming a uniform density of (n) ignitions, the area in square feet available to a single fire for spread before coalescence is

$$A_S = \frac{A \times (5280)^2}{n} \quad . \tag{ID. 1}$$

Also,

$$A_S(t) = \int_0^t r(t)\, dt \quad . \tag{ID. 2}$$

If $r(t) = K_1$ (Case 1),

$$A_S(t) = K_1 t \quad . \tag{ID. 3}$$

Equating (ID. 1) and (ID. 3) yields, for Case 1,

$$n_c = \frac{A \times (5280)^2}{K_1 t} \quad , \tag{ID. 4}$$

---

* At coalescence all of the individual fires have merged into a single large fire, and it is assumed that no regions within the area remain unburned.

where n_c represents the approximate number of initial fires required for coalescence by time t. The approximation results from geometric assumptions inherent in Eq. (ID. 4).

In Case 2,

$$r = K_2 t \quad , \tag{ID. 5}$$

and Eq. (ID. 2) becomes

$$A_S(t) = \int_0^t K_2 t \, dt = \frac{1}{2} K_2 t^2 \quad . \tag{ID. 6}$$

Equations (ID. 1) and (ID. 6) yield the approximation

$$n_c = \frac{2A \times (5280)^2}{K_2 t^2} \quad , \tag{ID. 7}$$

for spread Case 2.

APPENDIX II

RATIONALE FOR SENSITIVITY ANALYSIS

II. 1 Purpose

To examine the sensitivity of the radial inrush wind velocity, as calculated in Appendix IA, to variations in seven selected parameters, expressions for the partial derivatives $\frac{\partial v_w}{\partial \mu_i}$ have been developed, where $\mu_1 = n$, $\mu_2 = A$, $\mu_3 = FL$, $\mu_4 = E_{fuel}$, $\mu_5 = E_{frac,viol}$, $\mu_6 = E_{frac,resid}$, and $\mu_7 = r$.

II. 2 Partial Derivatives

Formulae for the partial derivatives with respect to selected parameters have been derived as follows:

For convenience, let us represent Eq. (IA. 1) as

$$v_w = Q_1 \cdot Q_2 \cdot Q_3 \tag{II. 1}$$

where

$$Q_1 = \left(\frac{88}{1000}\right)\left(\frac{50}{1089}\right)^{1/3}, \tag{II. 2}$$

$$Q_2 = \frac{[(n)(FL)(E_{fuel})]^{1/3}}{A^{1/6}}, \tag{II. 3}$$

and

$$Q_3 = \left\{ \frac{A_{SV}(r,t,\Delta t_V) \cdot E_{frac,viol}}{\Delta t_V} + \frac{A_{SR}(r,t,\Delta t_V,\Delta t_R) \cdot E_{frac,resid}}{\Delta t_R} \right\}^{1/3}. \tag{II. 4}$$

Then

$$\frac{\partial v_w}{\partial n} = Q_1 Q_3 \frac{[(FL)(E_{fuel})]^{1/3}}{3n^{2/3} A^{1/6}} , \quad \text{(II. 5)}$$

$$\frac{\partial v_w}{\partial A} = \frac{Q_1 Q_3 [(n)(FL)(E_{fuel})]^{1/3}}{-6 A^{7/6}} , \quad \text{(II. 6)}$$

$$\frac{\partial v_w}{\partial (FL)} = \frac{Q_1 Q_3 [(n)(E_{fuel})]^{1/3}}{3(FL)^{2/3} A^{1/6}} , \quad \text{(II. 7)}$$

$$\frac{\partial v_w}{\partial (E_{fuel})} = \frac{Q_1 Q_3 [(n)(FL)]^{1/3}}{3(E_{fuel})^{2/3} A^{1/6}} , \quad \text{(II. 8)}$$

$$\frac{\partial v_w}{\partial (E_{frac,\,viol})} = \frac{Q_1 Q_2}{3(Q_3)^2} \left(\frac{A_{SV}(r,t,\Delta t_V)}{\Delta t_V} - \frac{A_{SR}(r,t,\Delta t_V, \Delta t_R)}{\Delta t_R} \right) , \quad \text{(II. 9)}$$

and

$$\frac{\partial v_w}{\partial (E_{frac,\,resid})} = \frac{Q_1 Q_2}{3(Q_3)^2} \left(\frac{A_{SR}(r,t,\Delta t_V, \Delta t_R)}{\Delta t_R} - \frac{A_{SV}(r,t,\Delta t_V)}{\Delta t_V} \right) . \quad \text{(II. 10)}$$

Note that

$$\frac{\partial v_w}{\partial (E_{frac,\,viol})} = - \frac{\partial v_w}{\partial (E_{frac,\,resid})} . \quad \text{(II. 11)}$$

For Case 1, if $t \leq \Delta t_V$,

$$\frac{\partial v_w}{\partial r} = \frac{Q_1 Q_2}{3(Q_3)^2} \left(\frac{t \cdot E_{frac,\,viol}}{\Delta t_V} \right) . \quad \text{(II. 12)}$$

If $\Delta t_V < t \leq \Delta t_V + \Delta t_R$,

$$\frac{\partial v_w}{\partial r} = \frac{Q_1 Q_2}{3(Q_3)^2} \left[E_{frac,viol} + \frac{(t - \Delta t_V) \cdot E_{frac,resid}}{\Delta t_R} \right] , \quad \text{(II. 13)}$$

and if $t > \Delta t_V + \Delta t_R$,

$$\frac{\partial v_w}{\partial r} = \frac{Q_1 Q_2}{3(Q_3)^2} \left(E_{frac,viol} + E_{frac,resid} \right) . \quad \text{(II. 14)}$$

Since

$$E_{frac,viol} + E_{frac,resid} = 1 , \quad \text{(II. 15)}$$

then

$$\frac{\partial v_w}{\partial r} = \frac{Q_1 Q_2}{3(Q_3)^2} . \quad \text{(II. 16)}$$

For Case 2, if $t \leq \Delta t_V$,

$$\frac{\partial v_w}{\partial r} = \frac{Q_1 Q_2}{6(Q_3)^2} \left(\frac{t \cdot E_{frac,viol}}{\Delta t_V} \right) . \quad \text{(II. 17)}$$

If $\Delta t_V < t \leq \Delta t_V + \Delta t_R$,

$$\frac{\partial v_w}{\partial r} = \frac{Q_1 Q_2}{6(Q_3)^2} \left\{ \left[2 - (\Delta t_V / t) \right] E_{frac,viol} + \left[\frac{t - 2\Delta t_V + (\Delta t_V^2 / t)}{\Delta t_R} \right] E_{frac,resid} \right\} , \quad \text{(II. 18)}$$

and if $t > \Delta t_V + \Delta t_R$,

$$\frac{\partial v_w}{\partial r} = \frac{Q_1 Q_2}{6(Q_3)^2} \left\{ \left[2 - (\Delta t_V / t) \right] E_{frac,viol} + \left[2 - \frac{2(\Delta t_V) + \Delta t_R}{t} \right] E_{frac,resid} \right\} . \quad \text{(II. 19)}$$

II. 3 Input Parameters

Calculations have been made of $\frac{\partial v_w}{\partial \mu_i}$, $i = 1, \cdots, 7$, using fixed representative values of μ_j $(j \neq i)$ and varying μ_i across a range. Representative values, ranges, and points of calculation are listed in Table II-I.

II. 4 Method of Calculations

A computer program was written based upon Eqs. (II. 2), $\cdots$, (II. 19) and run using the input parameters as defined in Table II-I. A listing of this program and a sample of its output is included in Appendix III.

Appendix V contains seven sets of sensitivity curves based upon the output of this program. Each set represents $\frac{\partial v_w}{\partial \mu_i}$ plotted as a function of μ_i for each time value.

TABLE II - I

INPUT VALUES FOR SENSITIVITY ANALYSIS

Parameter	Representative Value	Range	Points
n_d	4500	2K - 10K	2K, 3K, 4K, 4.5K, 5K, 6K, 7K, and 10K
FL	15.0 T/Ac	5 - 30 T/Ac	5, 15.0, 30 T/Ac
E_{fuel}	7000 Btu/lb	6000 - 9000	6K, 7K, 8K, 9K
A	15.0 mi^2	1.0 - 25.0 mi^2	1.0, 5.0, 10.0 15.0, 25.0 mi^2
t	--	(Same as in Section IA. 4)	
Δt_V	360 sec	--	--
r	(Case 2-b)		
M	.01 ft/sec	.005 - .2 ft/sec	.005, .01, .015, .2
L	.1 ft/sec	--	--
K_1	5.0 ft^2/sec	--	--
A_{SV}	(Use Table IA-II)		
$E_{frac, viol}$	0.4	0.2 - 0.8	0.2, 0.4, 0.6, 0.8
Δt_R	4200 sec	--	--
A_{SR}	(Use Table IA-II)		
$E_{frac, resid}$	0.6	0.2 - 0.8	0.2, 0.4, 0.6, 0.8

APPENDIX III

COMPUTER PROGRAM FOR INRUSH WIND AND SENSITIVITY CALCULATIONS

III. 1 General

The following program is in two parts. Part I calculates v_w as a function of time and n for each combination of the other input variables as defined in Section IA. 4. Part II calculates $\frac{\partial v_w}{\partial \mu_i}$ $(i = 1, \cdots, 7)$ as a function of μ_i and time, with μ_j $(j \neq i)$ held constant, as discussed in Section II. 4. The inputs for Part II are listed in Table II-I. The program is written in FORTRAN IV for an IBM System/360 Model 40G digital computer.

III. 2 Data Cards

Thirteen data cards are required. The first six data cards contain the input data for Part I of the program. Card 1 has format 8F10. 4 and contains the following variables:

Columns	Parameter	Program Symbol	Units
1-10	E_{fuel}	EF	Btu/lb
11-20	Δt_V	DTV	seconds
21-30	Δt_R	DTR	seconds
31-40	$E_{frac, viol}$	EFV	number
41-50	$E_{frac, resid}$	EFR	number

Card 2 has format 3F10.6 and contains, in cols. 1-10, the rate of area spread in square feet per second; in cols. 11-20, the rate of perimeter increase in feet per second; and in cols. 21-30, the rate of radial increase in feet per second.

Card 3 has format 8F10.4 and contains three values of fuel loading in tons per acre.

Card 4 has format 8F10.4 and contains five values of area in square miles.

Card 5 has format 8I8 and contains eight values of initial ignition density (n_d) in number per square mile.

Cards 6 and 7 have format 8F10.4 and contain ten values of time in seconds.

Card 8 has format 8I8 and is a flag card. If one wishes to perform the sensitivity calculations of Part II, an integer 2 should be put in col. 8. If one wishes to omit the sensitivity calculations, an integer 1 should be put in col. 8.

The last five cards contain the additional inputs needed for Part II of the program. Card 7 has format I8, 6F10.4 and contains the representative values of the seven μ_i arranged in the following manner:

Columns	Parameter	Program Symbol	Units
1- 8	Rep. value of n_d	NDR	number
9-18	Rep. value of A	AR	square miles
19-28	Rep. value of FL	FLR	tons/acre
29-38	Rep. value of E_{fuel}	EFP	Btu/lb
39-48	Rep. value of $E_{frac, viol}$	EFVR	number
49-58	Rep. value of $E_{frac, resid}$	EFRR	number
59-68	Rep. value of M	AMR	feet/second

Cards 10-13 have format 4F10.5 and contain the points across the range of the four μ_i which were used as constant in Part I.

Card	Parameter	Program Symbol	No. of Points	Units
8	E_{fuel}	EF2(I)	4	Btu/lb
9	$E_{frac, viol}$	EFV2(I)	4	number
10	$E_{frac, resid}$	EFR2(I)	4	number
11	M (radial spread rate)	AM2(I)	4	feet/second

III.3 Program Listing

(See following pages.)

```
      DIMENSION A(5),T(10),N(8),CN(8),FL(3),NC(10),ND(8),VW(10,8),TM(10)
      DIMENSION EF2(4),EFV2(4),EFR2(4),AM2(4),ASVR(10),ASRR(10),Q3(10)
     $,PVW(8,10),NA(8)
C       PART ONE CALCULATES THE SET OF RADIAL INDRAFT WIND VELOCITIES
C     RESULTING FROM 8 VALUES OF N, THE NUMBER OF INITIAL FIRES, AT 10
C     GIVEN TIMES AFTER IGNITION. THIS SET IS PRODUCED FOR COMBINATIONS
C     OF 3 FUEL LOADINGS, 5 AREAS, AND 3 TYPES OF FIRE SPREAD.
C       THE FOLLOWING ARE INPUT VARIABLES:
C     EF, ENERGY CONTENT OF FUEL (BTU/POUND); DTV, VIOLENT BURNING TIME
C     (SECONDS); EFV, VIOLENT BURNING FRACTION; DTR, RESIDUAL BURNING TIME
C     (SECONDS); EFR, RESIDUAL BURNING FRACTION; AK, RATE OF AREA CHANGE,
C     (SQUARE  FEET/SEC); AL, RATE OF PERIMETER CHANGE (FEET/SEC); AM,
C     RATE OF RADIUS CHANGE (FEET/SEC); FL(3), FUEL LOADINGS (TONS/ACRE);
C     A(5), AREAS (SQUARE MILES); ND(8), NUMBER OF INITIAL FIRES PER SQUAR
C     MILE (NUMBER/MILES SQUARED); T(10), TIMES AFTER IGNITION (SECONDS).
1       FORMAT (8F10.4)
2       FORMAT (8I8)
3       FORMAT (3F10.6)
        READ (1,1) EF,DTV,DTR,EFV,EFR
        READ (1,3) AK,AL,AM
        READ (1,1) (FL(I),I=1,3)
        READ (1,1) (A(I),I=1,5)
        READ (1,2) (ND(I),I=1,8)
        READ (1,1) (T(I),I=1,10)
        AK2=(AL*AL)/6.28318
        AK3=(AM*AM)*6.28318
        FMF=2.78784E+07
        EDV=EFV/DTV
        EDR=EFR/DTR
        DTVR=DTV+DTR
C     ICASE INDICATES WHICH TYPE OF FIRE SPREAD IS BEING USED:
C     1 = CONSTANT AREA CHANGE; 2 = CONSTANT PERIMETER CHANGE;
C     3 = CONSTANT RADIAL CHANGE.
        DO 45 ICASE=1,3
        IF (ICASE-2) 6,4,5
4       CONST=AK2
        GO TO 6
5       CONST=AK3
C   M INDEXES OVER THE 3 FUEL LOADINGS.  L INDEXES OVER THE 5 AREAS
6       DO 45 M=1,3
        DO 45 L=1,5
        DO 7 I=1,8
        N(I)=ND(I)*A(L)
7       CN(I)=N(I)**(1.0/3.0)
        AA=((FL(M)*EF)**(1.0/3.0))/(A(L)**(1.0/6.0))*.031501
C     STATEMENTS 8-15 COMPUTE VELOCITIES FOR ICASE=1.
        IF (ICASE-1) 8,8,16
8       R=AK
        DO 15 K=1,10
        TIME=T(K)
        IF (TIME-DTV) 9,9,10
9       ASV=R*TIME
```

```
      ASR=0.0                                                           53
      ASBO=0.0                                                          54
      GO TO 13                                                          55
10    IF (TIME-DTVR) 11,11,12                                           56
11    ASV=R*DTV                                                         57
      ASR=R*(TIME-DTV)                                                  58
      ASBO=0.0                                                          59
      GO TO 13                                                          60
12    ASV=R*DTV                                                         61
      ASR=R*DTR                                                         62
      ASBO=R*(TIME-DTVR)                                                63
13    AAA=AA*((ASV*EDV+ASR*EDR)**(1.0/3.0))                             64
      DO 14 I=1,8                                                       65
14    VW(K,I)=AAA*CN(I)                                                 66
15    NC(K)=A(L)/(AK*TIME)*FMF                                          67
      GO TO 24                                                          68
C   STATEMENTS 16-23 COMPUTE VELOCITIES FOR ICASE=2 OR 3.               69
16    DO 23 K=1,10                                                      70
      TIME=T(K)                                                         71
      R=CONST*TIME                                                      72
      RH=R/2.0                                                          73
      IF (TIME-DTV) 17,17,18                                            74
17    ASV=RH*TIME                                                       75
      ASR=0.0                                                           76
      ASBO=0.0                                                          77
      GO TO 21                                                          78
18    IF (TIME-DTVR) 19,19,20                                           79
19    ASV=RH*(DTV*(2.0-(DTV/TIME)))                                     80
      ASR=RH*(TIME-DTV*(2.0-DTV/TIME))                                  81
      ASBO=0.0                                                          82
      GO TO 21                                                          83
20    ASV=RH*DTV*(2.0-DTV/TIME)                                         84
      ASR=RH*DTR*(2.0-(2.0*DTV+DTR)/TIME)                               85
      ASBO=RH*(TIME-DTVR*(2.0-DTVR/TIME))                               86
21    AAA=AA*((ASV*EDV+ASR*EDR)**(1.0/3.0))                             87
      DO 22 I=1,8                                                       88
22    VW(K,I)=AAA*CN(I)                                                 89
23    NC(K)=(2.0*A(L))/(CONST*TIME*TIME)*FMF                            90
24    WRITE (3,25)                                                      91
25    FORMAT ('1',T39,'VW IS THE RADIAL INDRAFT WIND VELOCITY IN MILES P  92
     $ER HOUR'/'0',T23,'N IS THE NUMBER OF INITIAL FIRES, NC IS THE REQU  93
     $IRED N FOR COALESCENCE BY THE GIVEN TIME'/)                        94
      C=DTV/60.0                                                        95
      B=DTR/60.0                                                        96
      WRITE (3,26) EF,EFV,EFR,C,B                                       97
26    FORMAT ('0',T41,'ENERGY CONTENT OF THE FUEL IS ',F9.1,' BTU PER PO  98
     $UND'//'0',T9,'VIOLENT BURNING FRACTION IS ',F6.2,T85,'RESIDUAL BUR  99
     $NING FRACTION IS ',F6.2/1X,T9,'VIOLENT BURNING TIME IS ',F6.2,' MI  100
     $NUTES',T85,'RESIDUAL BURNING TIME IS ',F6.2,' MINUTES'/)          101
      IF (ICASE-2) 27,28,29                                             102
27    WRITE (3,30) AK                                                   103
      GO TO 33                                                          104
```

```
28     WRITE (3,31) AL                                                    105
       GO TO 33                                                           106
29     WRITE (3,32) AM                                                    107
30     FORMAT ('0',T32,'CASE 1, CONSTANT AREA INCREASE, K = ',E13.6,' (SQ  108
      $UARE FEET/SECOND)'//)                                              109
31     FORMAT ('0',T33,'CASE 2A, CONSTANT PERIMETER INCREASE, L = '       110
      $,E13.6,' (FEET/SECOND)'//)                                         111
32     FORMAT ('0',T34,'CASE 2B, CONSTANT RADIAL INCREASE, M = ',E13.6,'  112
      $(FEET/SECOND)'//)                                                  113
33     WRITE (3,34) A(L),FL(M)                                            114
34     FORMAT ('0',T26,'AREA = ',F10.4,' SQUARE MILES ',10X,' FUEL LOADIN  115
      $G = ',F10.4,' TONS PER ACRE'//)                                    116
       DO 35 I=1,10                                                       117
35     TM(I)=T(I)/60.0                                                    118
       DO 40 II=1,2                                                       119
       IF (II-1) 36,36,37                                                 120
36     IA=1                                                               121
       IB=5                                                               122
       GO TO 38                                                           123
37     IA=6                                                               124
       IB=10                                                              125
38     WRITE (3,41) (TM(I),I=IA,IB)                                       126
       WRITE (3,42)                                                       127
       DO 39 K=1,8                                                        128
39     WRITE (3,43) (N(K),VW(I,K),I=IA,IB)                                129
40     WRITE (3,44) (NC(I),I=IA,IB)                                       130
41     FORMAT ('0',T4,5(4X,' FOR ',F6.1,' MINUTES ')/)                    131
42     FORMAT ('0',T4,5(6X,'N',11X,'VW',4X)//)                            132
43     FORMAT (1X,T4,5(3X,I6,2X,E13.6))                                   133
44     FORMAT ('0',T4,5(7X,'NC =',I10,3X)////)                            134
45     CONTINUE                                                           135
       READ (1,2) N2                                                      136
       IF (N2-2) 103,46,103                                               137
C      PART TWO CALCULATES THE PARTIAL DERIVATIVES WITH RESPECT TO THE    138
C    FOLLOWING VARIABLES: N,A,FL,EF,EFV,EFR,R. EACH PARTIAL IS EVALUATED  139
C    FOR ALL THE INPUT VALUES OF THE VARIABLE AND AT EACH OF THE TIMES    140
C    USED IN PART ONE.                                                    141
C      ADDITIONAL INPUT NEEDED FOR PART TWO IS:                           142
C    NDR,AR,FLR,EFP,EFVR,EFRR,AMR (THESE ARE MOST PROBABLE OR REPRESENTAT 143
C    VALUES FOR THE VARIABLES FOR WHICH THE PARTIALS ARE EVALUATED.)      144
C    EF2(4), ENERGY CONTENT OF THE FUEL(BTU/POUND); EFV2(4), VIOLENT      145
C    BURNING FRACTION; EFR2(4), RESIDUAL BURNING FRACTION; AM2(4), RATE   146
C    OF RADIAL INCREASE(FEET/SEC).                                        147
46     READ (1,47) NDR,AR,FLR,EFP,EFVR,EFRR,AMR                           148
47     FORMAT (I8,6F10.2)                                                 149
       READ (1,48) (EF2(I),I=1,4)                                         150
       READ (1,48) (EFV2(I),I=1,4)                                        151
       READ (1,48) (EFR2(I),I=1,4)                                        152
       READ (1,48) (AM2(I),I=1,4)                                         153
48     FORMAT (4F10.5)                                                    154
C    THROUGH 53 CALCULATES Q3, THE PART OF THE PARTIALS WHICH IS ONLY      155
C    TIME-DEPENDENT                                                       156
```

```
      AK2=AMR*AMR*6.28318                                                  157
      DO 53 K=1,10                                                         158
      TIME=T(K)                                                            159
      RRH=AK2*TIME/2.0                                                     160
      IF (TIME-DTV) 49,49,50                                               161
49    ASVR(K)=RRH*TIME                                                     162
      ASRR(K)=0.0                                                          163
      GO TO 53                                                             164
50    IF (TIME-DTVR) 51,51,52                                              165
51    ASVR(K)=RRH*(DTV*(2.0-DTV/TIME))                                     166
      ASRR(K)=RRH*(TIME-DTV*(2.0-DTV/TIME))                                167
      GO TO 53                                                             168
52    ASRR(K)=RRH*(DTR*(2.0-((2.0*DTV+DTR)/TIME)))                         169
      ASVR(K)=RRH*(DTV*(2.0-DTV/TIME))                                     170
53    Q3(K)=((ASVR(K)*EFVR/DTV)+(ASRR(K)*EFRR/DTR))**(1.0/3.0)             171
C   PARTIALS WITH RESPECT TO N(NUMBER OF INITIAL FIRES) FOR 8 N            172
      BB=.031501*((FLR*EFP)**(1.0/3.0)/(3.0*(AR**(1.0/6.0))))             173
      DO 54 I=1,8                                                          174
      BBB=BB/(ND(I)*AR)**(2.0/3.0)                                         175
      DO 54 K=1,10                                                         176
54    PVW(I,K)=BBB*Q3(K)                                                   177
55    FORMAT ('1',T40,'PARTIAL DERIVATIVES OF THE RADIAL INDRAFT WIND VE   178
     $LOCITY')                                                             179
56    FORMAT (1X,T44,'WITH RESPECT TO N, THE NUMBER OF INITIAL FIRES')     180
57    FORMAT (1X,T31,'FOR CASE 2B, CONSTANT RADIAL INCREASE, M = '         181
     $,E13.6,' FEET PER SECOND'//)                                         182
58    FORMAT ('0',T4,'WITH AREA = ',F10.5,' SQUARE MILES     FUEL LOADIN   183
     $G = ',F10.4,' TONS PER ACRE     ENERGY OF FUEL = ',F10.4,' BTU PER  184
     $ POUND')                                                             185
59    FORMAT (1X,T9,'VIOLENT BURNING FRACTION = ',F6.2,T85,'RESIDUAL BUR   186
     $NING FRACTION = ',F6.2)                                              187
60    FORMAT (1X,T9,'VIOLENT BURNING TIME = ',F6.2,' MINUTES',T85,'RESID   188
     $UAL BURNING TIME = ',F6.2,' MINUTES'////)                            189
61    FORMAT ('0',T15,'N =',8(3X,I8,3X))                                   190
62    FORMAT ('0',T3,F6.1,' MINUTES ',8(1X,E13.6))                         191
      WRITE (3,55)                                                         192
      WRITE (3,56)                                                         193
      WRITE (3,57) AMR                                                     194
      WRITE (3,58) AR,FLR,EFP                                              195
      WRITE (3,59) EFVR,EFRR                                               196
      WRITE (3,60) C,B                                                     197
      DO 63 I=1,8                                                          198
63    NA(I)=ND(I)*AR                                                       199
      WRITE (3,61) (NA(I),I=1,8)                                           200
      DO 64 K=1,10                                                         201
64    WRITE (3,62) TM(K),(PVW(I,K),I=1,8)                                  202
C   PARTIALS WITH RESPECT TO A(AREA) FOR 5 A                               203
      BB=.031501*(FLR*EFP)**(1.0/3.0)                                      204
      DO 65 I=1,5                                                          205
      BBB=BB*(NDR*AR)**(1.0/3.0)/(-6.0*A(I)**(7.0/6.0))                    206
      DO 65 K=1,10                                                         207
65    PVW(I,K)=BBB*Q3(K)                                                   208
```

```
      NR=NDR*AR                                                          209
      WRITE (3,55)                                                       210
      WRITE (3,66)                                                       211
66    FORMAT (1X,T51,'WITH RESPECT TO A, THE TOTAL AREA')                212
      WRITE (3,57) AMR                                                   213
      WRITE (3,67) NR,FLR,EFP                                            214
67    FORMAT ('0',T4,'WITH INITIAL NUMBER OF FIRES = ',I8,3X,'FUEL LOADI 215
     $NG = ',F10.4,' TONS PER ACRE',3X,'ENERGY OF FUEL = ',F10.4,' BTU P 216
     $ER POUND')                                                         217
      WRITE (3,59) EFVR,EFRR                                             218
      WRITE (3,60) C,B                                                   219
      WRITE (3,69) (A(I),I=1,5)                                          220
      DO 68 K=1,10                                                       221
68    WRITE (3,70) TM(K),(PVW(I,K),I=1,5)                                222
69    FORMAT ('0',T19,'A =',5(8X,F10.5,2X)/1X,T13,' (SQUARE MILES)'//)   223
70    FORMAT ('0',T7,F6.1,' MINUTES ',5(7X,E13.6))                       224
C   PARTIALS WITH RESPECT TO FL(FUEL LOADING) FOR 3 FL                   225
      BB=.031501*(NDR*AR*EFP)**(1.0/3.0)/(3.0*AR**(1.0/6.0))             226
      DO 71 I=1,3                                                        227
      BBB=BB/FL(I)**(2.0/3.0)                                            228
      DO 71 K=1,10                                                       229
71    PVW(I,K)=BBB*Q3(K)                                                 230
      WRITE (3,55)                                                       231
      WRITE (3,72)                                                       232
72    FORMAT (1X,T49,'WITH RESPECT TO FL, THE FUEL LOADING')             233
      WRITE (3,57) AMR                                                   234
      WRITE (3,73) NR,AR,EFP                                             235
73    FORMAT ('0',T4,'WITH INITIAL NUMBER OF FIRES = ',I8,5X,'AREA = '   236
     $,F10.5,' SQUARE MILES',5X,'ENERGY OF FUEL = ',F10.4,' BTU PER POUN 237
     $D')                                                                238
      WRITE (3,59) EFVR,EFRR                                             239
      WRITE (3,60) C,B                                                   240
      WRITE (3,75) (FL(I),I=1,3)                                         241
      DO 74 K=1,10                                                       242
74    WRITE (3,76) TM(K),(PVW(I,K),I=1,3)                                243
75    FORMAT ('0',T32,'FL =',3(11X,F10.4,2X)/1X,T26,'(TONS PER ACRE)'//) 244
76    FORMAT ('0',T22,F6.1,' MINUTES',3(10X,F13.6))                      245
C   PARTIALS WITH RESPECT TO EF(ENERGY CONTENT OF FUEL) FOR 4 EF         246
      BB=(.031501*(NDR*AR*FLR)**(1.0/3.0))/(3.0*AR**(1.0/6.0))           247
      DO 77 I=1,4                                                        248
      BBB=BB/EF2(I)**(2.0/3.0)                                           249
      DO 77 K=1,10                                                       250
77    PVW(I,K)=BBB*Q3(K)                                                 251
      Q12=.031501*(NDR*AR*FLR*EFP)**(1.0/3.0)/AR**(1.0/6.0)              252
      WRITE (3,55)                                                       253
      WRITE (3,78)                                                       254
78    FORMAT (1X,T42,'WITH RESPECT TO EF, THE ENERGY CONTENT OF THE FUEL 255
     $')                                                                 256
      WRITE (3,57) AMR                                                   257
      WRITE (3,79) NR,AR,FLR                                             258
79    FORMAT ('0',T4,'WITH INITIAL NUMBER OF FIRES = ',I8,5X,'AREA = '   259
     $,F10.5,' SQUARE MILES',5X,'FUEL LOADING = ',F10.4,' TONS PER ACRE' 260
```

```
     $)                                                                 261
      WRITE (3,59) EFVR,EFRR                                            262
      WRITE (3,60) C,B                                                  263
      WRITE (3,80) (EF2(I),I=1,4)                                       264
80    FORMAT ('0',T25,'EF =',4(11X,F10.5,2X)/1X,T17,'(BTU PER POUND)'//)  265
      DO 81 K=1,10                                                      266
81    WRITE (3,82) TM(K),(PVW(I,K),I=1,4)                               267
82    FORMAT ('0',T14,F6.1,' MINUTES ',4(10X,E13.6))                    268
C   PARTIALS WITH RESPECT TO EFV(VIOLENT BURNING FRACTION) FOR 4 EFV2   269
      DO 83 I=1,4                                                       270
      EFRC=1.0-EFV2(I)                                                  271
      DO 83 K=1,10                                                      272
      AAA=ASVR(K)/DTV                                                   273
      BBB=ASRR(K)/DTR                                                   274
83    PVW(I,K)=Q12*(AAA-BBB)/(3.0*(AAA*EFV2(I)+BBB*EFRC)**(2.0/3.0))    275
      WRITE (3,55)                                                      276
      WRITE (3,84)                                                      277
84    FORMAT (1X,T42,'WITH RESPECT TO EFV, THE VIOLENT BURNING FRACTION'  278
     $)                                                                 279
      WRITE (3,57) AMR                                                  280
      WRITE (3,79) NR,AR,FLR                                            281
      WRITE (3,85) EFP                                                  282
85    FORMAT (1X,T9,'ENERGY OF FUEL = ',F10.4,' BTU PER POUND',T85,'RESI  283
     $DUAL BURNING FRACTION = 1.0-EFV')                                 284
      WRITE (3,60) C,B                                                  285
      WRITE (3,87) (EFV2(I),I=1,4)                                      286
      DO 86 K=1,10                                                      287
86    WRITE (3,82) TM(K),(PVW(I,K),I=1,4)                               288
87    FORMAT ('0',T24,'EFV =',4(11X,F10.5,2X)//)                        289
C   PARTIALS WITH RESPECT TO EFR(RESIDUAL BURNING FRACTION) FOR 4 EFR2  290
      DO 88 I=1,4                                                       291
      EFVC=1.0-EFR2(I)                                                  292
      DO 88 K=1,10                                                      293
      BBB=ASRR(K)/DTR                                                   294
      AAA=ASVR(K)/DTV                                                   295
88    PVW(I,K)=Q12*(BBB-AAA)/(3.0*(AAA*EFVC+BBB*EFR2(I))**(2.0/3.0))    296
      WRITE (3,55)                                                      297
      WRITE (3,89)                                                      298
89    FORMAT (1X,T42,'WITH RESPECT TO EFR, THE RESIDUAL BURNING FRACTION  299
     $')                                                                300
      WRITE (3,57) AMR                                                  301
      WRITE (3,79) NR,AR,FLR                                            302
      WRITE (3,90) EFP                                                  303
90    FORMAT (1X,T9,'ENERGY OF FUEL =',F10.4,' BTU PER POUND',T85,'VIOLF  304
     $NT BURNING FRACTION = 1.0-EFR')                                   305
      WRITE (3,60) C,B                                                  306
      WRITE (3,92) (EFR2(I),I=1,4)                                      307
      DO 91 K=1,10                                                      308
91    WRITE (3,82) TM(K),(PVW(I,K),I=1,4)                               309
92    FORMAT ('0',T24,'EFR =',4(11X,F10.5,2X)//)                        310
C   PARTIALS WITH RESPECT TO R(CASE 2B) FOR 4 AM                        311
      Q123=Q12*EFVR/DTV                                                 312
```

```
      DO 97 I=1,4                                                       313
      CONST=AM2(I)*AM2(I)*6.28318                                       314
      DO 97 K=1,10                                                      315
      TIME=T(K)                                                         316
      R=CONST*TIME/2.0                                                  317
      IF (TIME-DTV) 93,93,94                                            318
93    PVW(I,K)=Q123*TIME/(6.0*(R*TIME*EFVR/DTV)**(2.0/3.0))             319
      GO TO 97                                                          320
94    IF (TIME-DTVR) 95,95,96                                           321
95    BB=Q12*((2.0-DTV/TIME)*EFVR+((TIME-DTV*(2.0-DTV/TIME))/DTR*EFRR))  322
      QQ=(R*(DTV*(2.0-DTV/TIME))*EFVR/DTV)+(R*(TIME-DTV*(2.0-DTV/TIME))  323
     $*EFRR/DTR)                                                        324
      PVW(I,K)=BB/(6.0*QQ**(2.0/3.0))                                   325
      GO TO 97                                                          326
96    BB=Q12*(((2.0-DTV/TIME)*EFVR)+((2.0-(DTVR+DTV)/TIME)*EFRR))       327
      QQ=(R*DTV*(2.0-DTV/TIME)*EFVR/DTV)+(R*(DTR*(2.0-(2.0*DTV+DTR)     328
     $/TIME))*EFRR/DTR)                                                 329
      PVW(I,K)=BB/(6.0*QQ**(2.0/3.0))                                   330
97    CONTINUE                                                          331
      WRITE (3,55)                                                      332
      WRITE (3,98)                                                      333
98    FORMAT (1X,T26,'WITH RESPECT TO R, THE RATE OF SPREAD, FOR CASE 2B  334
     $,R = 6.28*M**2*TIME')                                             335
      WRITE (3,99) AR,NR,FLR,EFP                                        336
99    FORMAT ('0',T14,'WITH AREA = ',F10.5,' SQUARE MILES',T75,'NUMBER O  337
     $F INITIAL FIRES = ',I8/1X,T19,'FUEL LOADING = ',F10.4,' TONS PER A  338
     $CRE',T75,'ENERGY OF FUEL = ',F10.5,' BTU PER POUND')              339
      WRITE (3,100) EFVR,EFRR,C,B                                       340
100   FORMAT (1X,T19,'VIOLENT BURNING FRACTION = ',F6.2,T75,'RESIDUAL BU  341
     $RNING FRACTION = ',F6.2/1X,T19,'VIOLENT BURNING TIME = ',F6.2,' MI  342
     $NUTES ',T75,'RESIDUAL BURNING TIME = ',F6.2,' MINUTES'////)       343
      WRITE (3,101) (AM2(I),I=1,4)                                      344
101   FORMAT ('0',T26,'M =',4(10X,E13.6)/1X,T18,'(FEET/SECOND)'//)      345
      DO 102 K=1,10                                                     346
102   WRITE (3,82) TM(K),(PVW(I,K),I=1,4)                               347
103   CONTINUE                                                          348
      STOP                                                              349
      END                                                               350
```

VW IS THE RADIAL INDRAFT WIND VELOCITY IN MILES PER HOUR

N IS THE NUMBER OF INITIAL FIRES, NC IS THE REQUIRED N FOR COALESCENCE BY THE GIVEN TIME

ENERGY CONTENT OF THE FUEL IS 7000.0 BTU PER POUND

VIOLENT BURNING FRACTION IS 0.40
VIOLENT BURNING TIME IS 6.00 MINUTES

RESIDUAL BURNING FRACTION IS 0.60
RESIDUAL BURNING TIME IS 70.00 MINUTES

CASE 28, CONSTANT RADIAL INCREASE, M = 0.100000E-01 (FEET/SECOND)

AREA = 15.0000 SQUARE MILES FUEL LOADING = 15.0000 TONS PER ACRE

FOR 2.0 MINUTES		FOR 4.0 MINUTES		FOR 6.0 MINUTES		FOR 8.0 MINUTES		FOR 16.0 MINUTES	
N	VW	N	VW	N	VW	N	VW	N	VW
30000	0.503696E 01	30000	0.799569E 01	30000	0.104773E 02	30000	0.124576E 02	30000	0.175383E 02
45000	0.576588E 01	45000	0.915277E 01	45000	0.119935E 02	45000	0.142604E 02	45000	0.200764E 02
60000	0.634617E 01	60000	0.100739E 02	60000	0.132006E 02	60000	0.156956E 02	60000	0.220969E 02
67500	0.660028E 01	67500	0.104773E 02	67500	0.137291E 02	67500	0.163241E 02	67500	0.229817E 02
75000	0.683620E 01	75000	0.108518E 02	75000	0.142199E 02	75000	0.169075E 02	75000	0.238032E 02
90000	0.726455E 01	90000	0.115318E 02	90000	0.151109E 02	90000	0.179669E 02	90000	0.252946E 02
105000	0.764759E 01	105000	0.121398E 02	105000	0.159076E 02	105000	0.189143E 02	105000	0.266283E 02
150000	0.861308E 01	150000	0.136724E 02	150000	0.179159E 02	150000	0.213022E 02	150000	0.299901E 02
NC = 92437344		NC = 23109344		NC = 10270817		NC = 5777334		NC = 1444334	

FOR 24.0 MINUTES		FOR 32.0 MINUTES		FOR 48.0 MINUTES		FOR 64.0 MINUTES		FOR 80.0 MINUTES	
N	VW	N	VW	N	VW	N	VW	N	VW
30000	0.210909E 02	30000	0.240408E 02	30000	0.290431E 02	30000	0.333834E 02	30000	0.373126E 02
45000	0.241431E 02	45000	0.275199E 02	45000	0.332460E 02	45000	0.382144E 02	45000	0.427122E 02
60000	0.265729E 02	60000	0.302896E 02	60000	0.365920E 02	60000	0.420604E 02	60000	0.470109E 02
67500	0.276369E 02	67500	0.315024E 02	67500	0.380572E 02	67500	0.437445E 02	67500	0.488933E 02
75000	0.286248E 02	75000	0.326284E 02	75000	0.394175E 02	75000	0.453082E 02	75000	0.506409E 02
90000	0.304183E 02	90000	0.346729E 02	90000	0.418873E 02	90000	0.481471E 02	90000	0.538140E 02
105000	0.320222E 02	105000	0.365011E 02	105000	0.440959E 02	105000	0.506857E 02	105000	0.566515E 02
150000	0.360649E 02	150000	0.411093E 02	150000	0.496629E 02	150000	0.570847E 02	150000	0.638036E 02
NC = 641926		NC = 361083		NC = 160481		NC = 90270		NC = 57773	

Fig. III-1
SAMPLE OUTPUT PAGE FROM PART I

PARTIAL DERIVATIVES OF THE RADIAL INDRAFT WIND VELOCITY
WITH RESPECT TO A, THE TOTAL AREA
FOR CASE 28, CONSTANT RADIAL INCREASE, M = 0.100000E-01 FEET PER SECOND

WITH INITIAL NUMBER OF FIRES = 67500 FUEL LOADING = 15.0000 TONS PER ACRE ENERGY OF FUEL = 7000.0000 BTU PER POUND
VIOLENT BURNING FRACTION = 0.40 RESIDUAL BURNING FRACTION = 0.60
VIOLENT BURNING TIME = 6.00 MINUTES RESIDUAL BURNING TIME = 70.00 MINUTES

A = (SQUARE MILES)	1.00000	5.00000	10.00000	15.00000	25.00000
2.0 MINUTES	-0.172753E 01	-0.264218E 00	-0.117696E 00	-0.733365E-01	-0.404108E-01
4.0 MINUTES	-0.274229E 01	-0.419420E 00	-0.186830E 00	-0.116415E 00	-0.641481E-01
6.0 MINUTES	-0.359341E 01	-0.549595E 00	-0.244817E 00	-0.152546E 00	-0.840577E-01
8.0 MINUTES	-0.427260E 01	-0.653473E 00	-0.291089E 00	-0.181379E 00	-0.999454E-01
16.0 MINUTES	-0.601514E 01	-0.919987E 00	-0.409808E 00	-0.255353E 00	-0.140707E 00
24.0 MINUTES	-0.723358E 01	-0.110634E 01	-0.492819E 00	-0.307077E 00	-0.169209E 00
32.0 MINUTES	-0.824532E 01	-0.126108E 01	-0.561748E 00	-0.350027E 00	-0.192876E 00
48.0 MINUTES	-0.996094E 01	-0.152348E 01	-0.678632E 00	-0.422858E 00	-0.233008E 00
64.0 MINUTES	-0.114495E 02	-0.175115E 01	-0.780049E 00	-0.486051E 00	-0.267830E 00
80.0 MINUTES	-0.127571E 02	-0.195726E 01	-0.871861E 00	-0.543260E 00	-0.299353E 00

Fig. III-2 SAMPLE OUTPUT PAGE FROM PART II

APPENDIX IV

RADIAL INRUSH WIND VELOCITY CURVES

The following 45 sets of curves are based upon the rationale and parameter values discussed in Appendix IA and are drawn from the output of Part I of the computer program listed in Appendix III.

Each curve on a page represents radial inrush wind velocity (v_w) as a function of the number of initial ignitions (n) for a specified time after ignition. Each family of curves shows ten different times with a specified combination of spread case, area, and fuel loading.

The curves are bounded above by the coalescence locus, as discussed in Appendix ID.

For all of the curves in this group, the fuel energy is taken as 7000 Btu/lb, the violent burning time as 6 minutes, the residual burning time as 70 minutes, the violent burning fraction as 0.4, and the residual burning fraction as 0.6 .

FREDERICK POST COMPANY
301TR20 CROSS SECTION 20 X 20 PER INCH

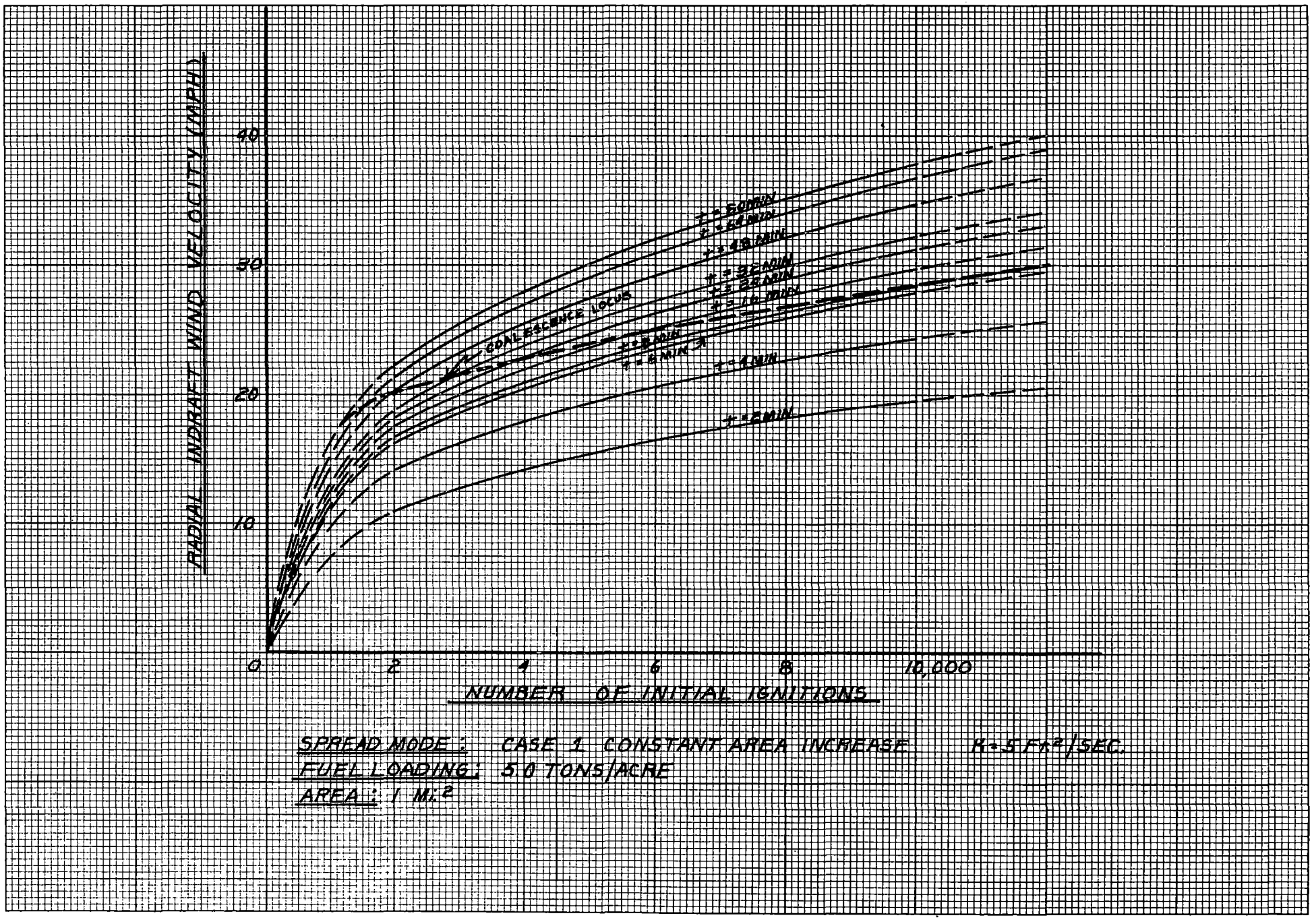

Fig. IV-1

FREDERICK POST COMPANY
301TR20 CROSS SECTION 20 X 20 PER INCH

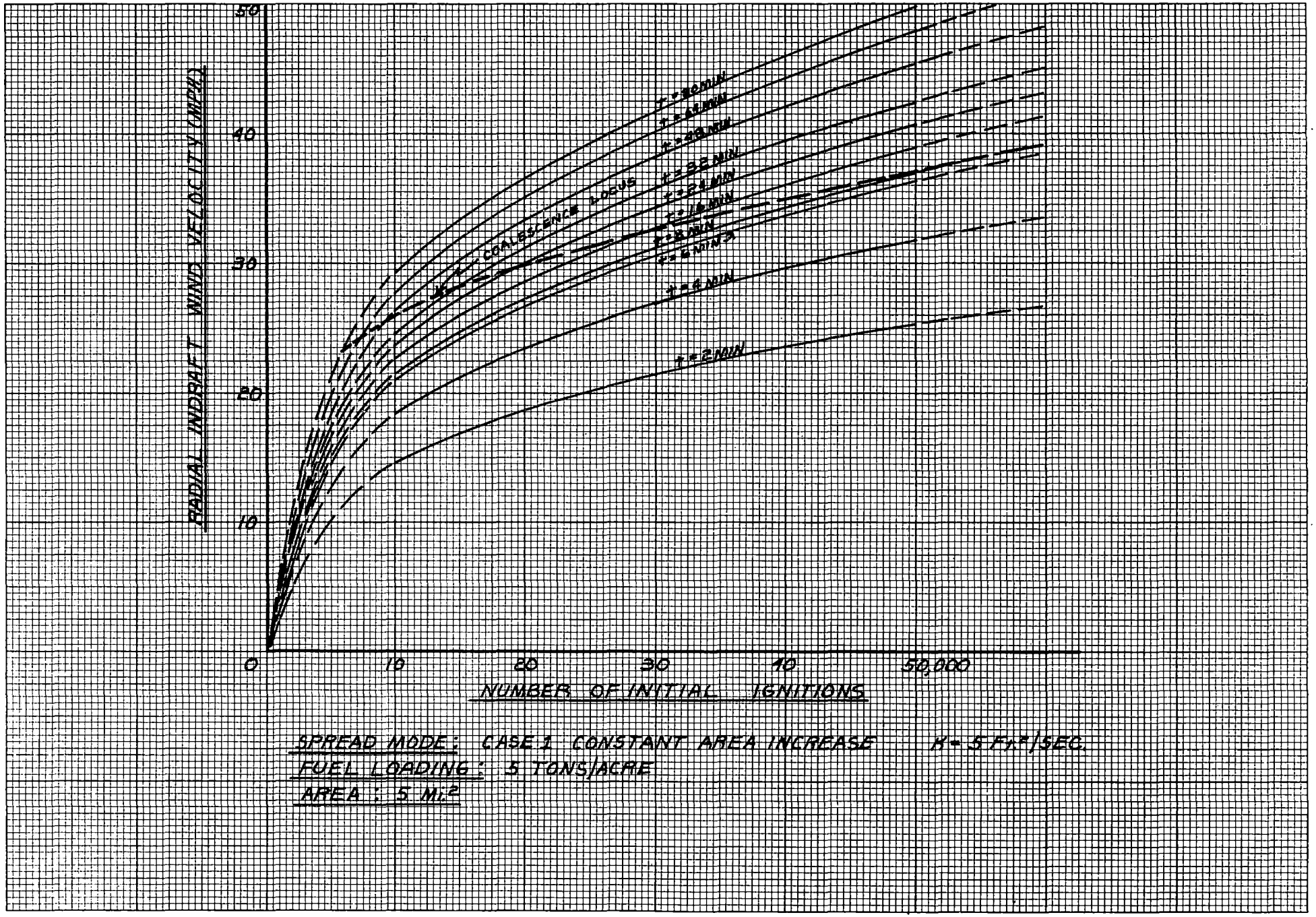

Fig. IV-2

10 TO CH 323
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.

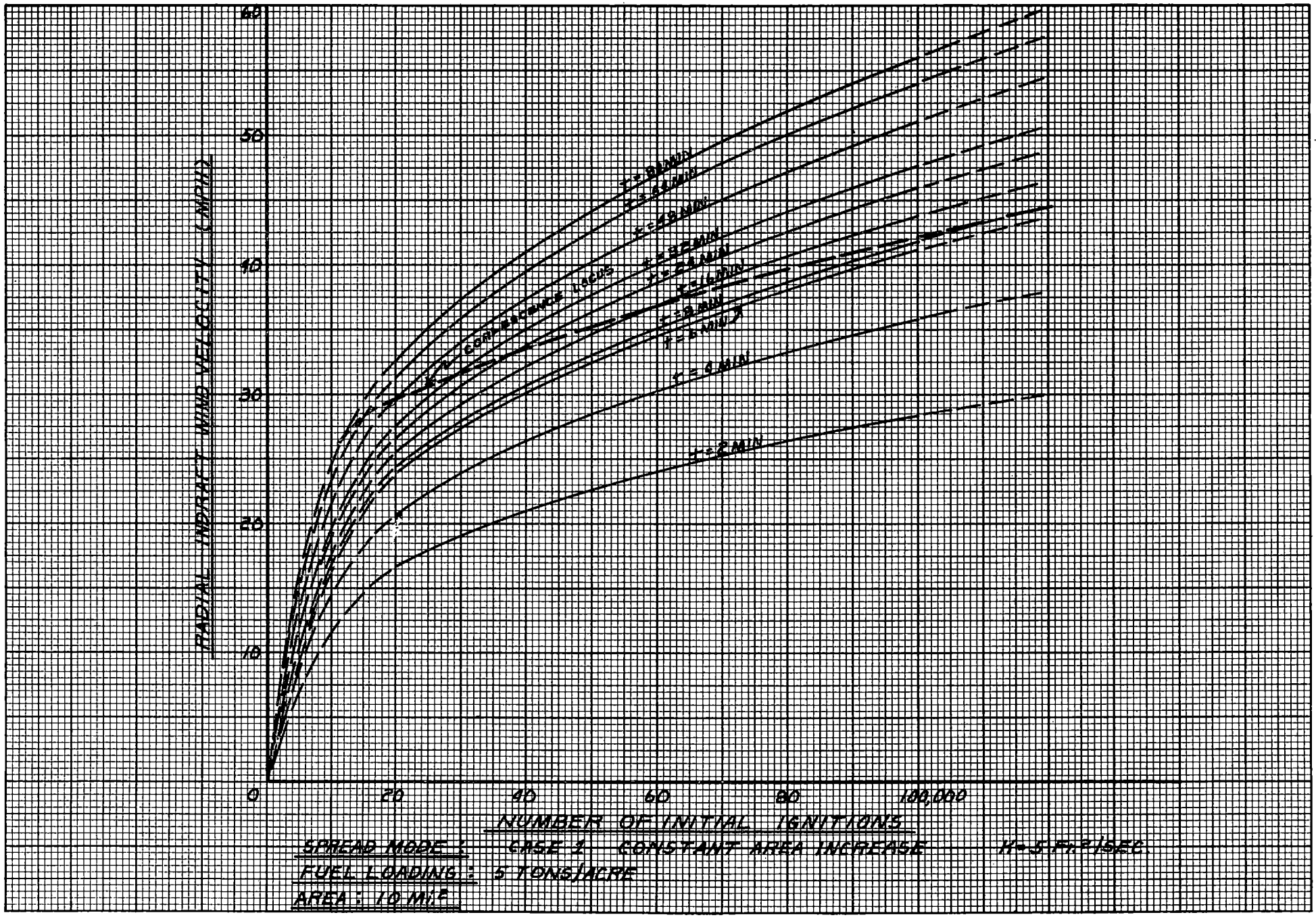

Fig. IV-3

FREDERICK POST COMPANY
301TR20 CROSS SECTION 20 X 20 PER INCH

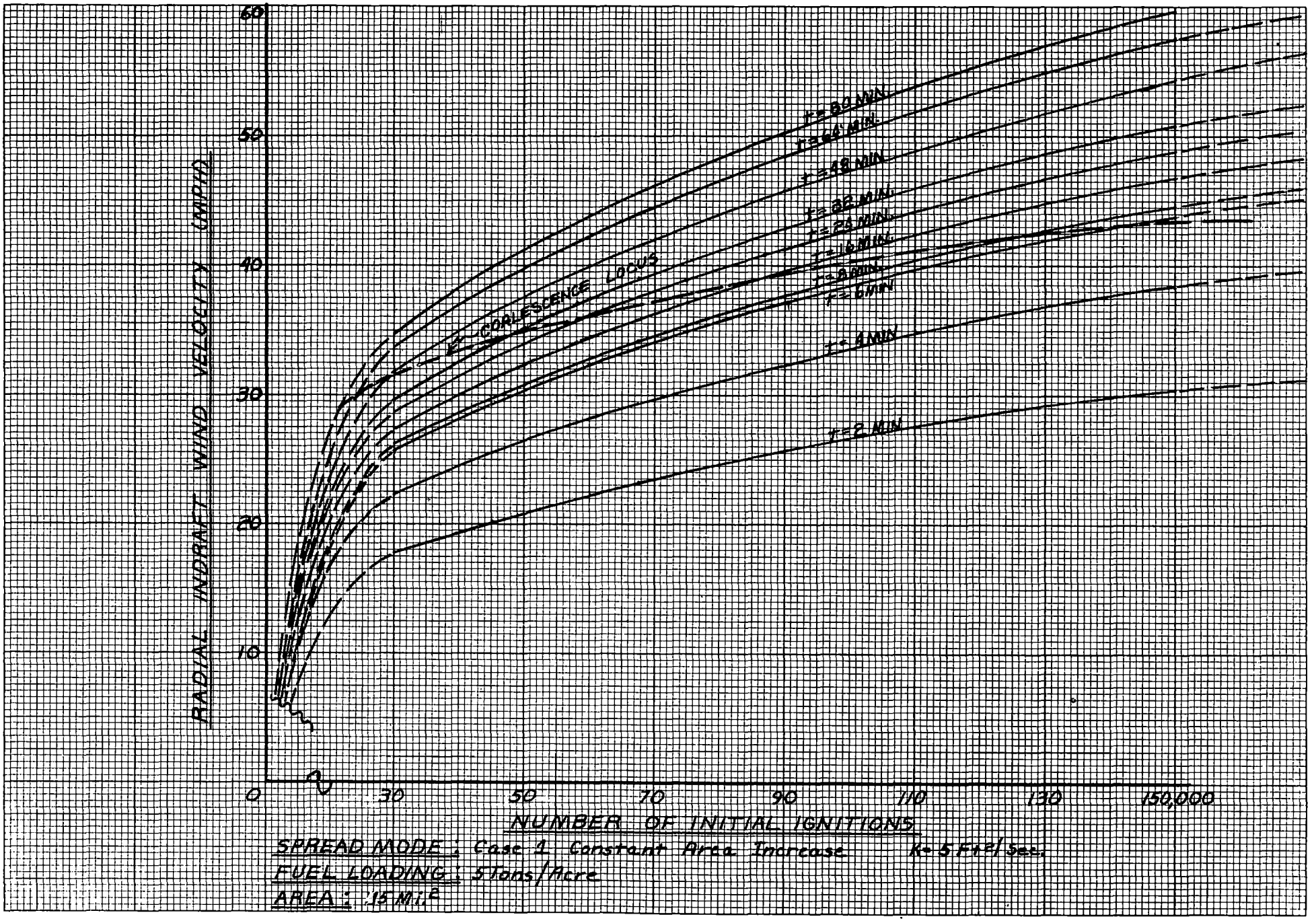

Fig. IV-4

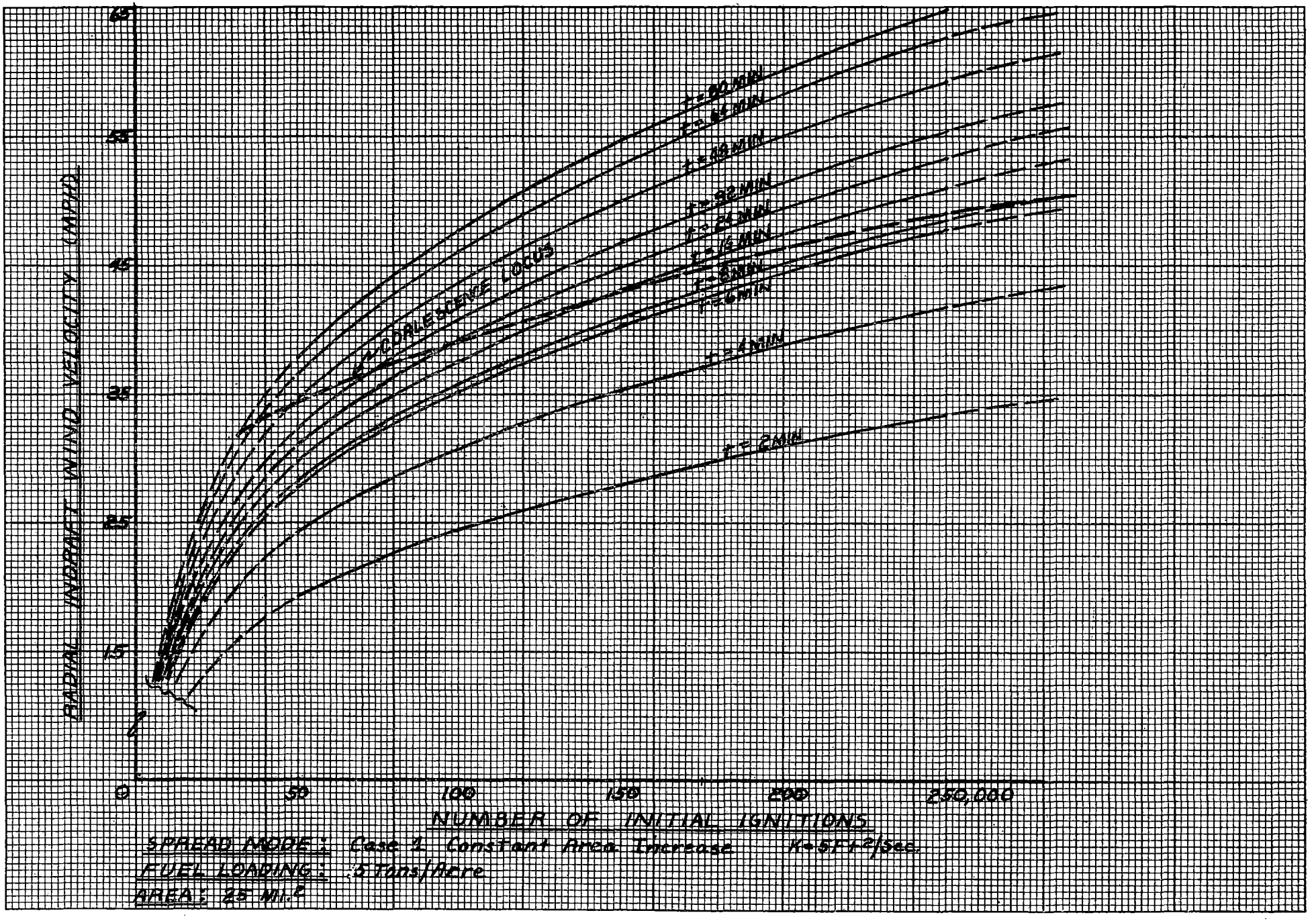
FREDERICK POST COMPANY
301TR20 CROSS SECTION 20 X 20 PER INCH
RADIAL INWARD WIND VELOCITY (MPH)
65
55
45
35
25
15
5
0
50
100
150
200
250,000
NUMBER OF INITIAL IGNITIONS
t=60 MIN
t=44 MIN
t=32 MIN
t=24 MIN
t=16 MIN
t=8 MIN
t=6 MIN
t=4 MIN
t=2 MIN
COALESCENCE LOCUS
SPREAD MODE: Case 1 Constant Area Increase K=5Ft²/sec.
FUEL LOADING: 5 Tons/Acre
AREA: 25 Mi.²

Fig. IV-5

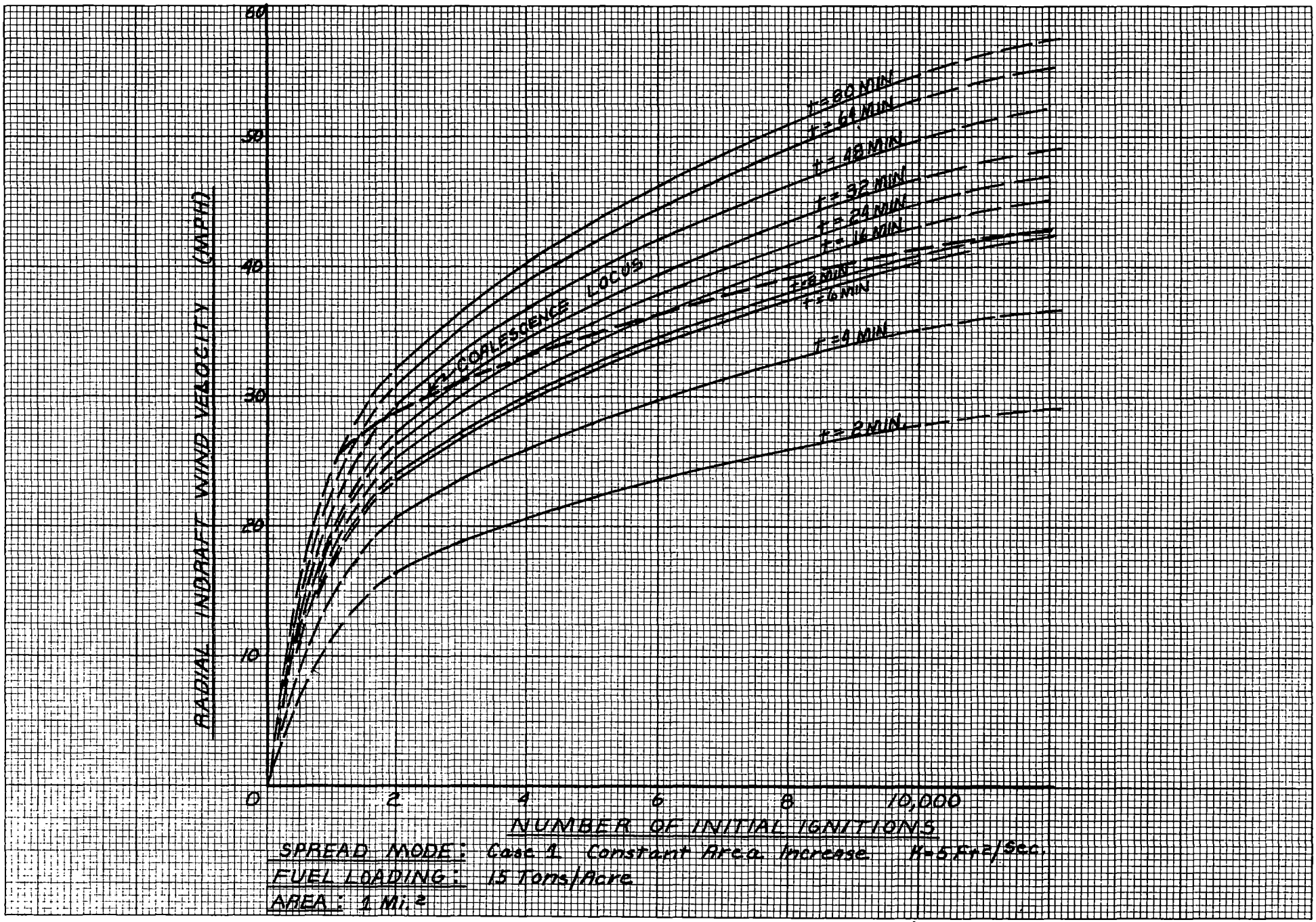
FREDERICK POST COMPANY
301-TR20 CROSS SECTION 20 X 20 PER INCH
RADIAL INDRAFT WIND VELOCITY (MPH)
60
50
40
30
20
10
0
2
4
6
8
10,000
NUMBER OF INITIAL IGNITIONS
t = 80 MIN
t = 64 MIN
t = 48 MIN
t = 32 MIN
t = 24 MIN
t = 16 MIN
t = 12 MIN
t = 8 MIN
t = 6 MIN
t = 4 MIN
t = 2 MIN
COALESCENCE LOCUS
SPREAD MODE: Case 1 Constant Area Increase K=5 Fr²/Sec.
FUEL LOADING: 15 Tons/Acre
AREA: 1 Mi.²

Fig. IV-6

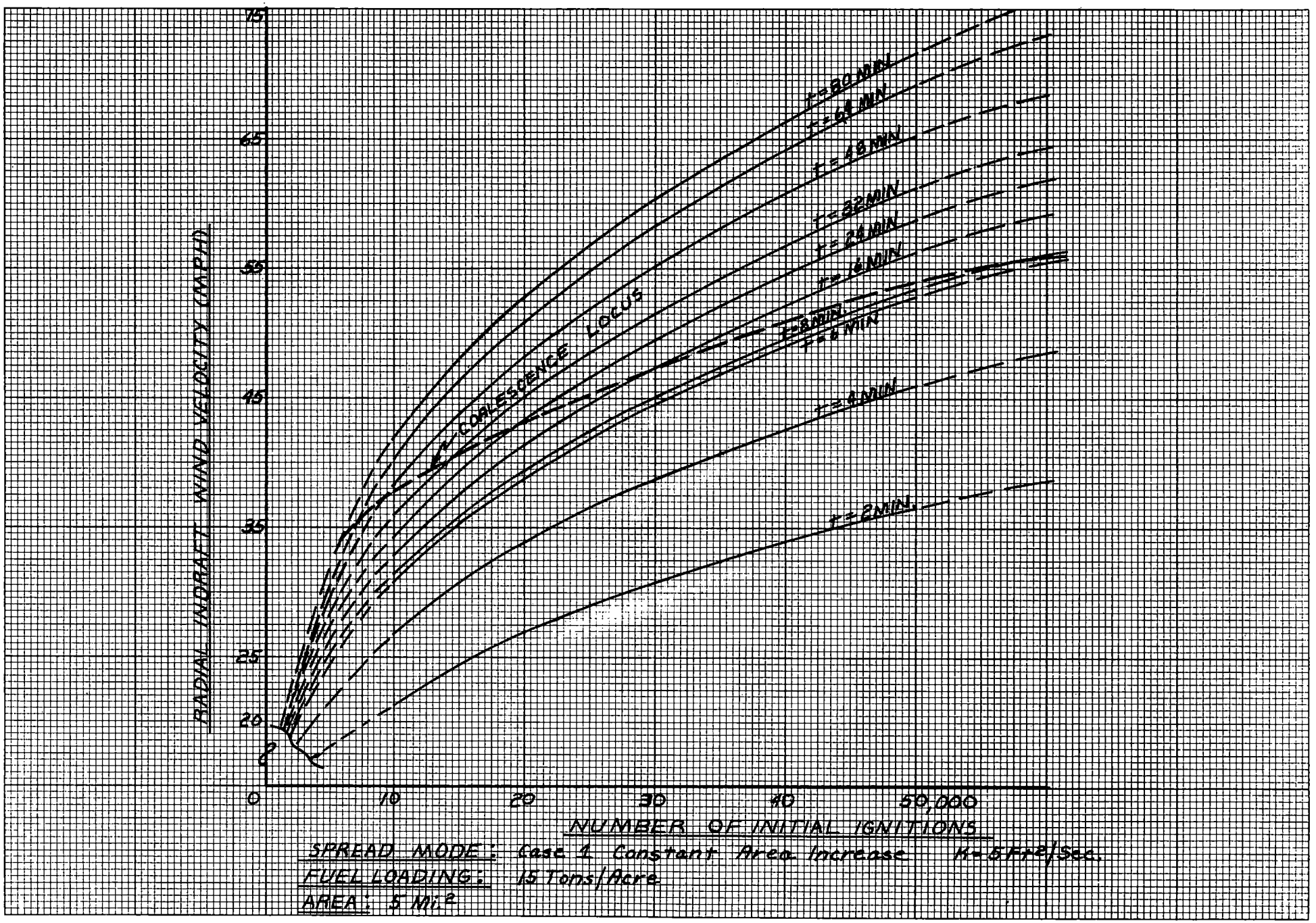
FREDERICK POST COMPANY
301TR20 CROSS SECTION 20 X 20 PER INCH
RADIAL INDRAFT WIND VELOCITY (MPH)
75
65
55
45
35
25
20
0
10
20
30
40
50,000
NUMBER OF INITIAL IGNITIONS
T=60 MIN
T=48 MIN
T=32 MIN
T=24 MIN
T=16 MIN
T=8 MIN
T=6 MIN
T=4 MIN
T=2 MIN
COALESCENCE LOCUS
SPREAD MODE: Case 1 Constant Area Increase K=.5Ft²/Sec.
FUEL LOADING: 15 Tons/Acre
AREA: 5 Mi²

Fig. IV-7

FREDERICK POST COMPANY
301TR20 CROSS SECTION 20 X 20 PER INCH

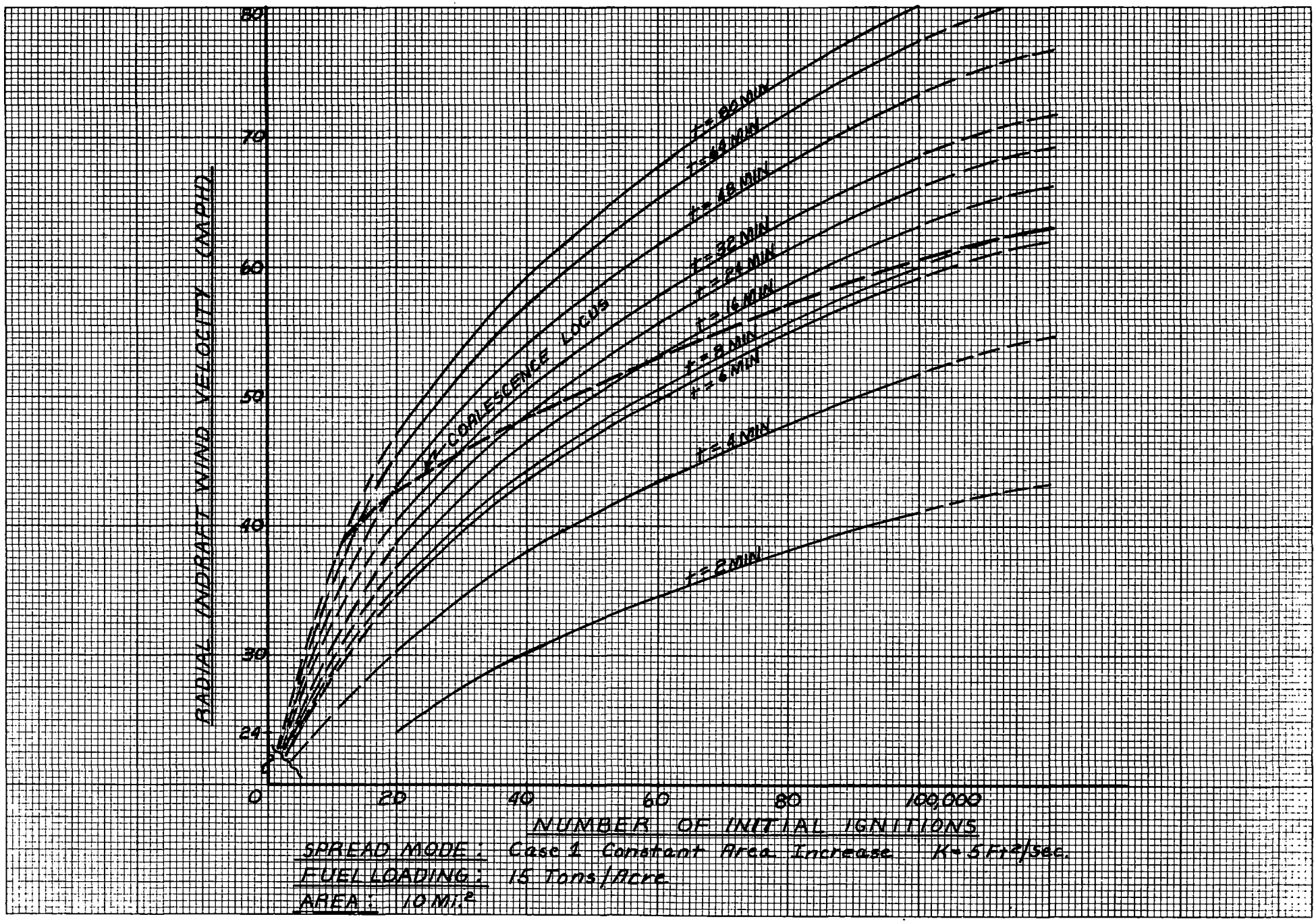

Fig. IV-8

FREDERICK POST COMPANY
301TR20 CROSS SECTION 20 X 20 PER INCH

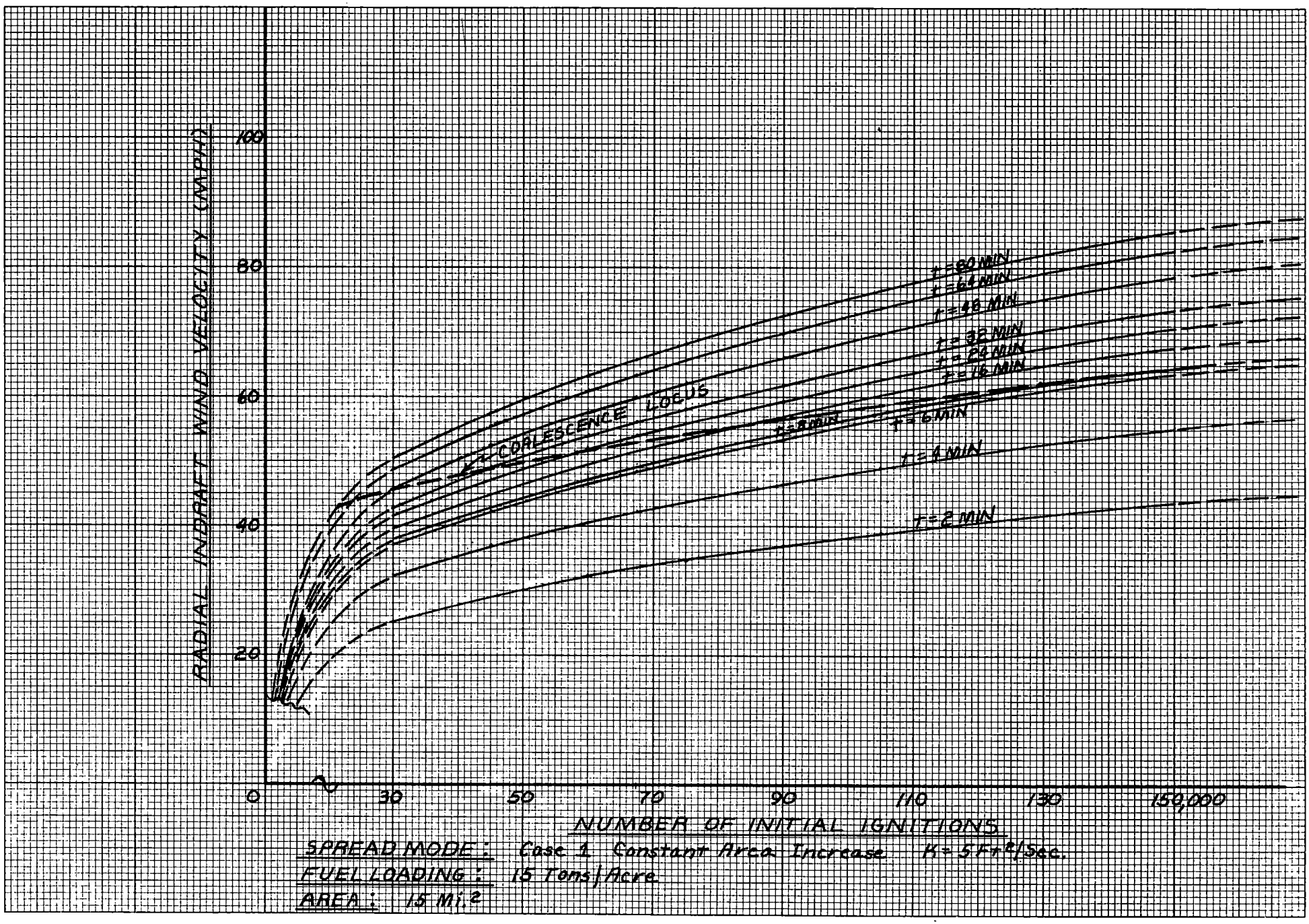

Fig. IV-9

FREDERICK POST COMPANY
301TR20 CROSS SECTION 20 X 20 PER INCH

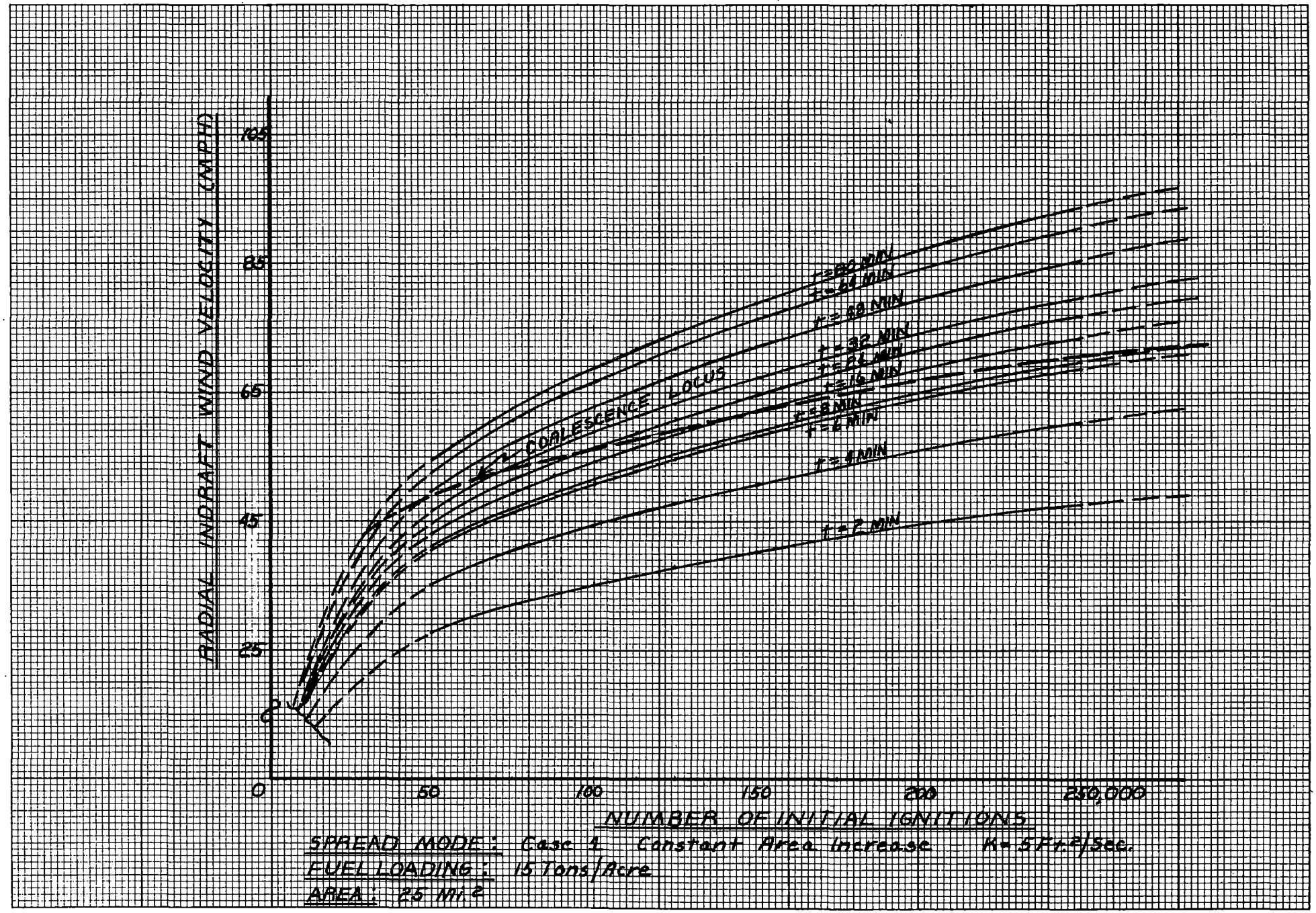

Fig. IV-10

FREDERICK POST COMPANY
301TR20 CROSS SECTION 20 X 20 PER INCH

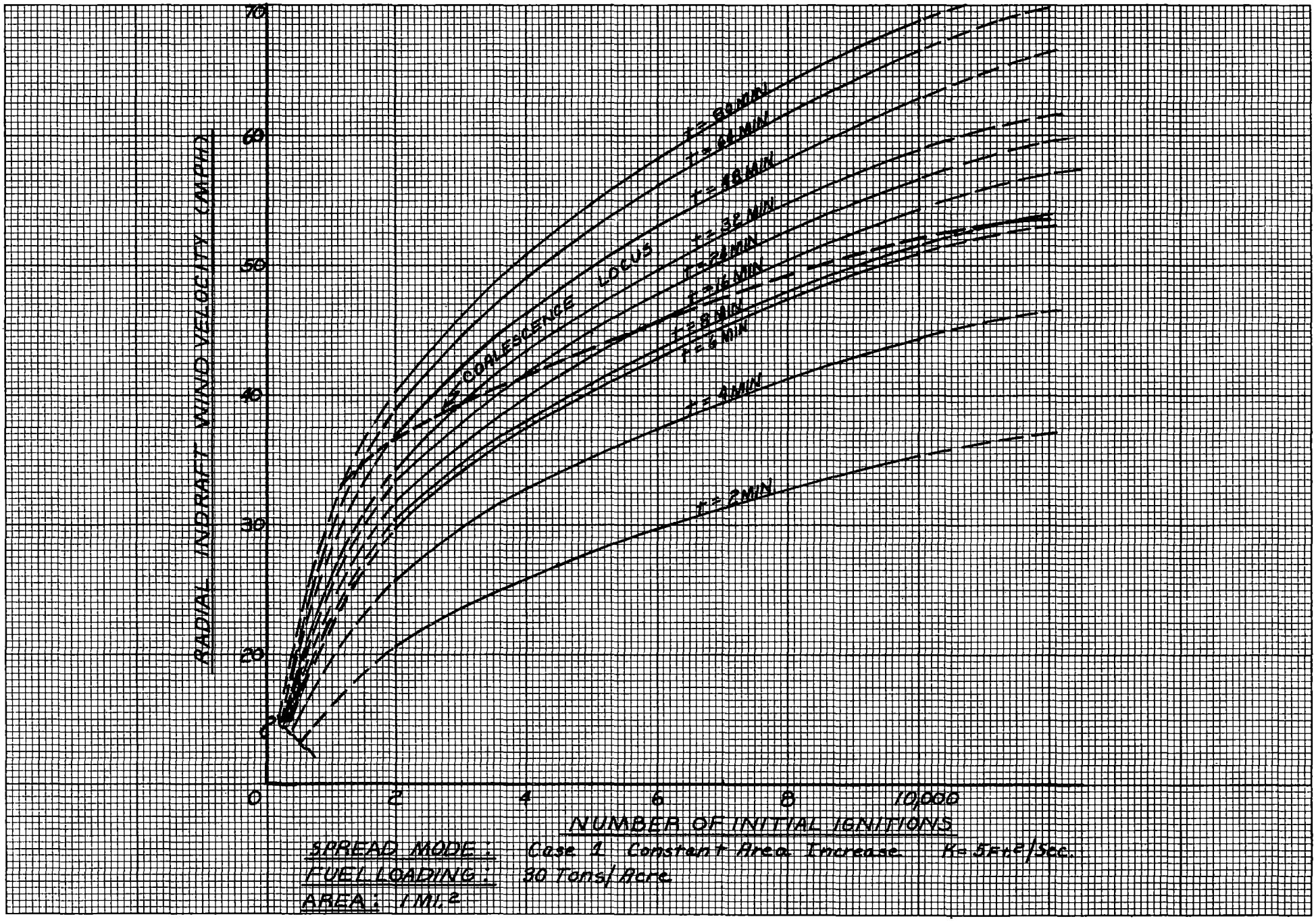

Fig. IV-11

FREDERICK POST COMPANY
301TR20 CROSS SECTION 20 X 20 PER INCH

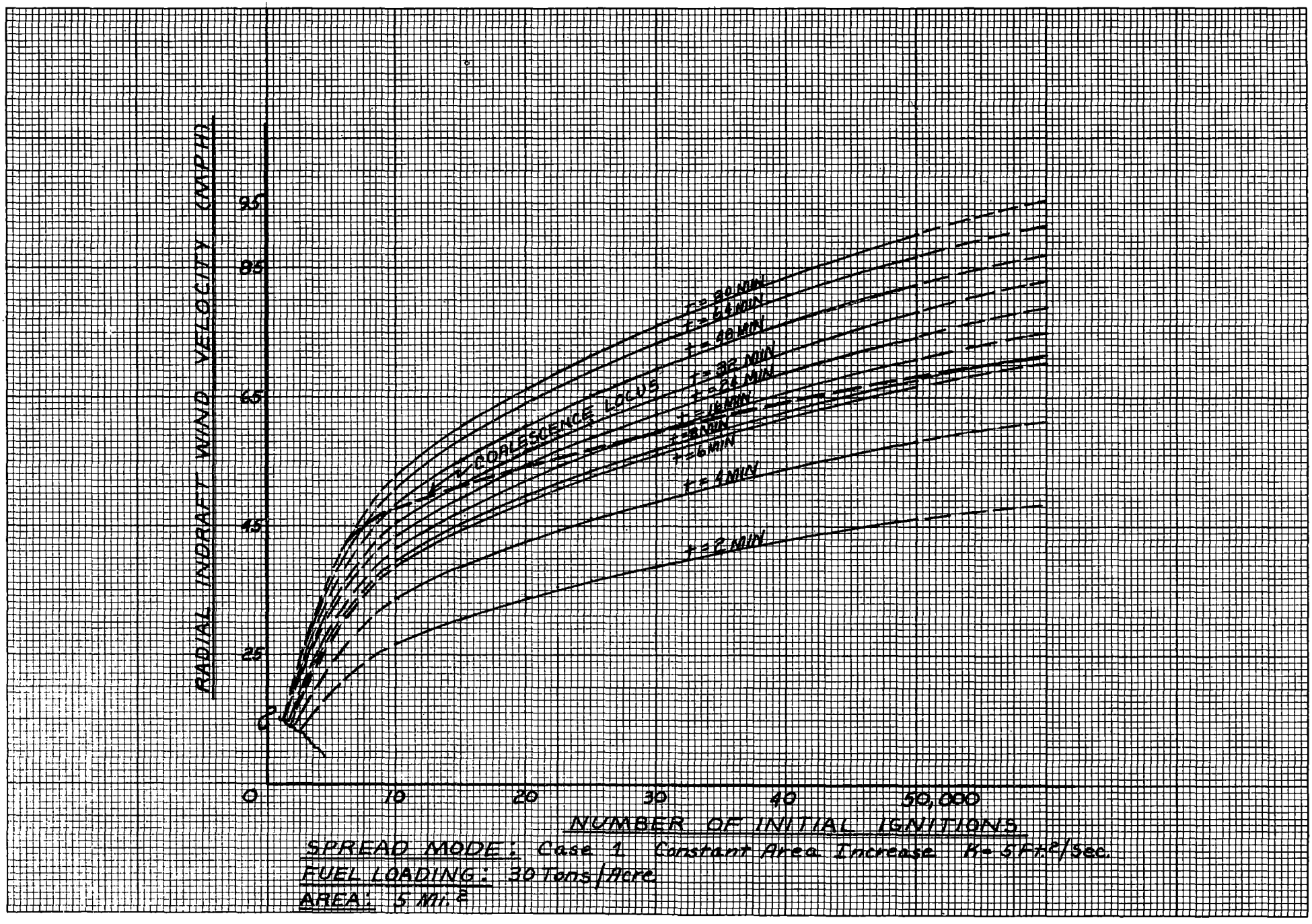

Fig. IV-12

FREDERICK POST COMPANY
301 TR20 CROSS SECTION 20 X 20 PER INCH

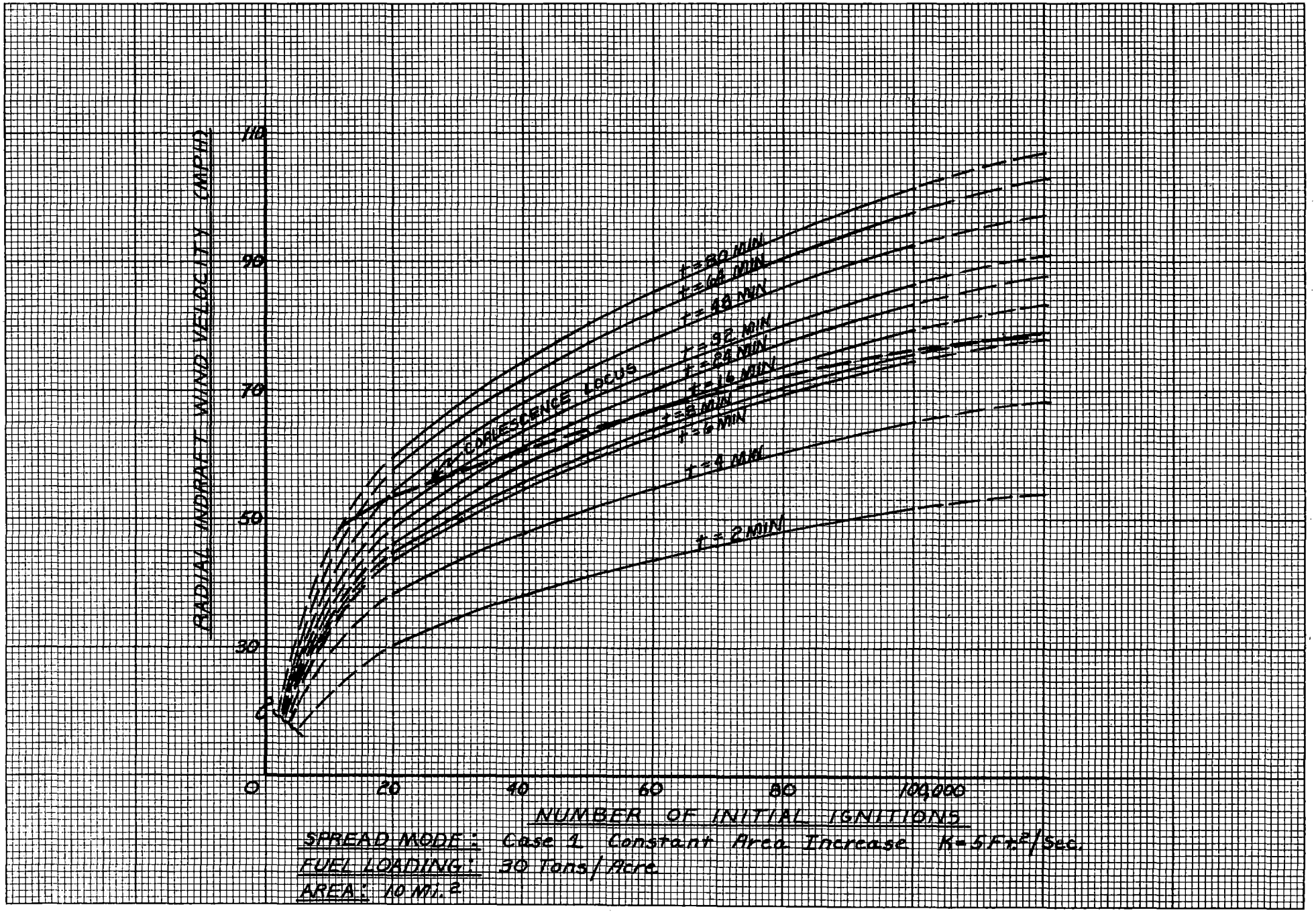

Fig. IV-13

FREDERICK POST COMPANY
301TR20 CROSS SECTION 20 X 20 PER INCH

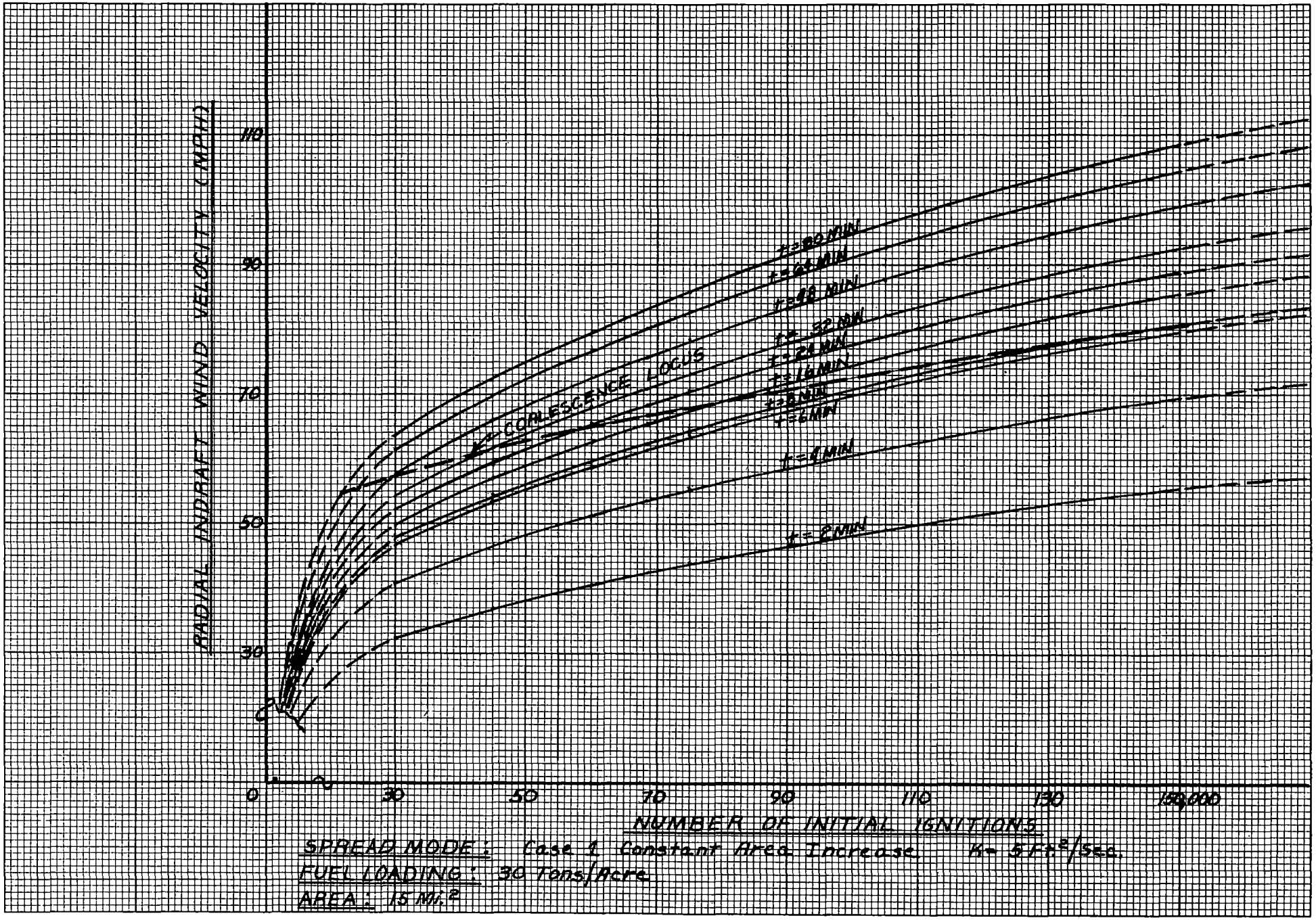

Fig. IV-14

FREDERICK POST COMPANY
301TR20 CROSS SECTION 20 X 20 PER INCH

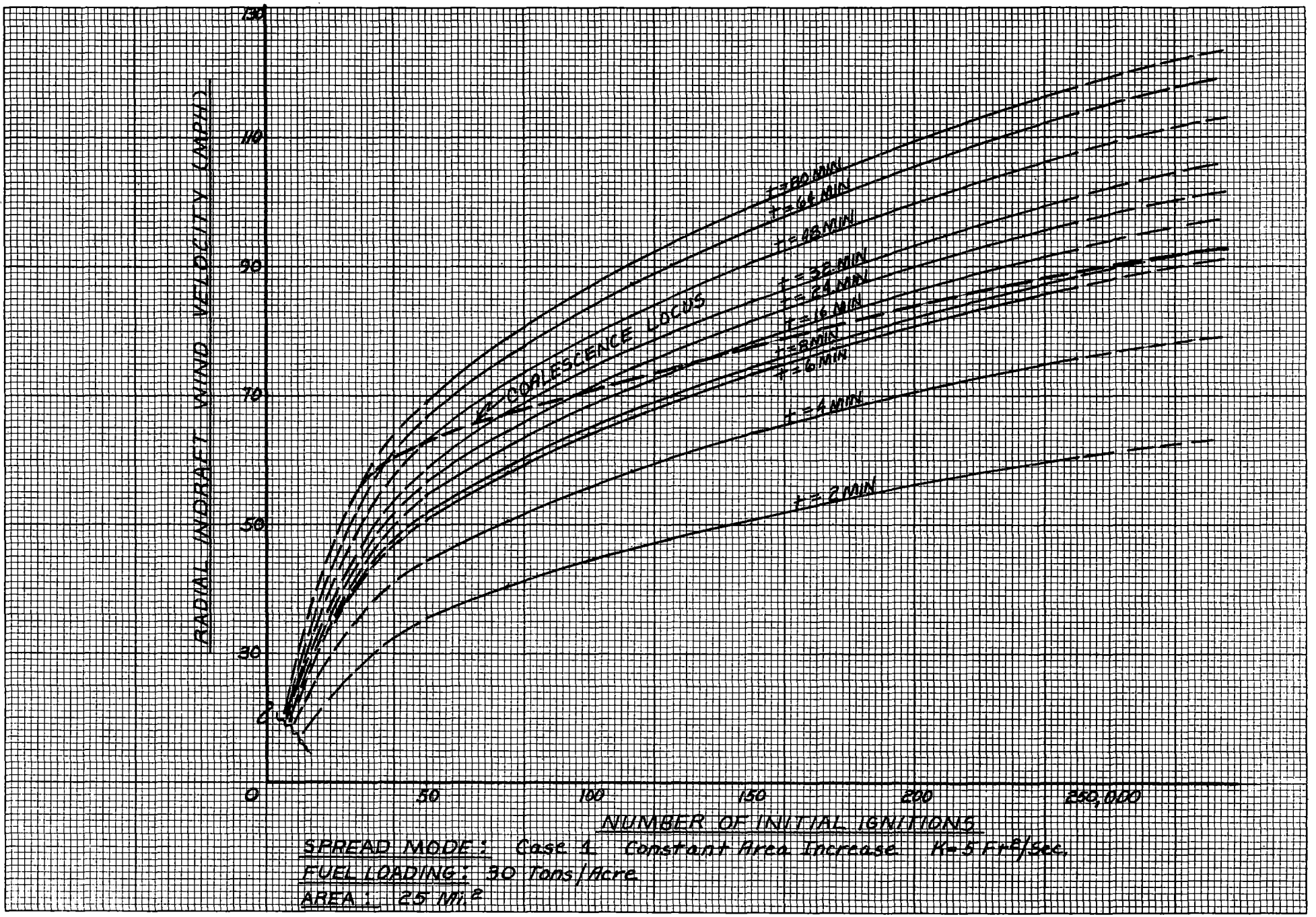

Fig. IV-15

FREDERICK POST COMPANY
301TR20 CROSS SECTION 20 X 20 PER INCH

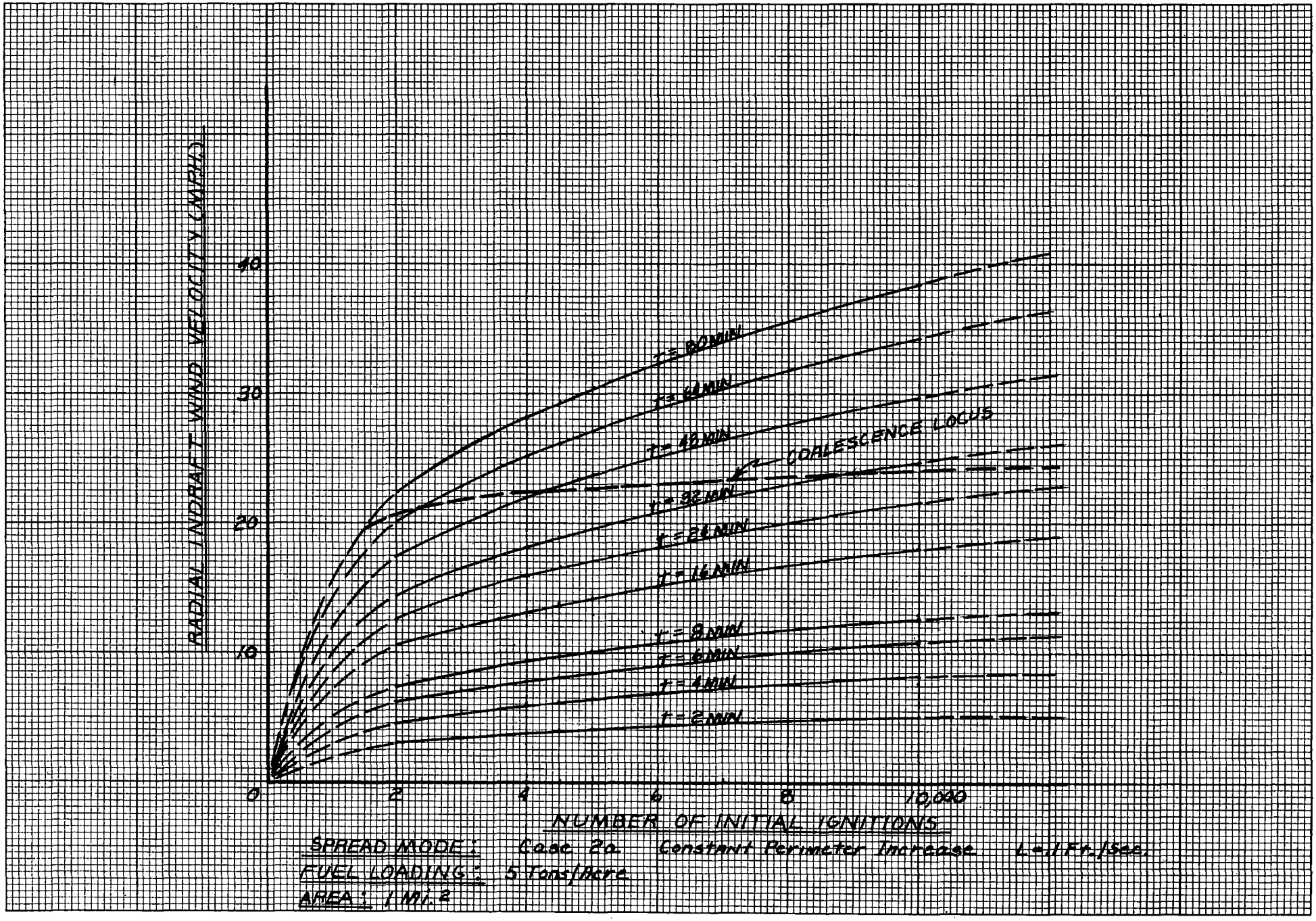

Fig. IV-16

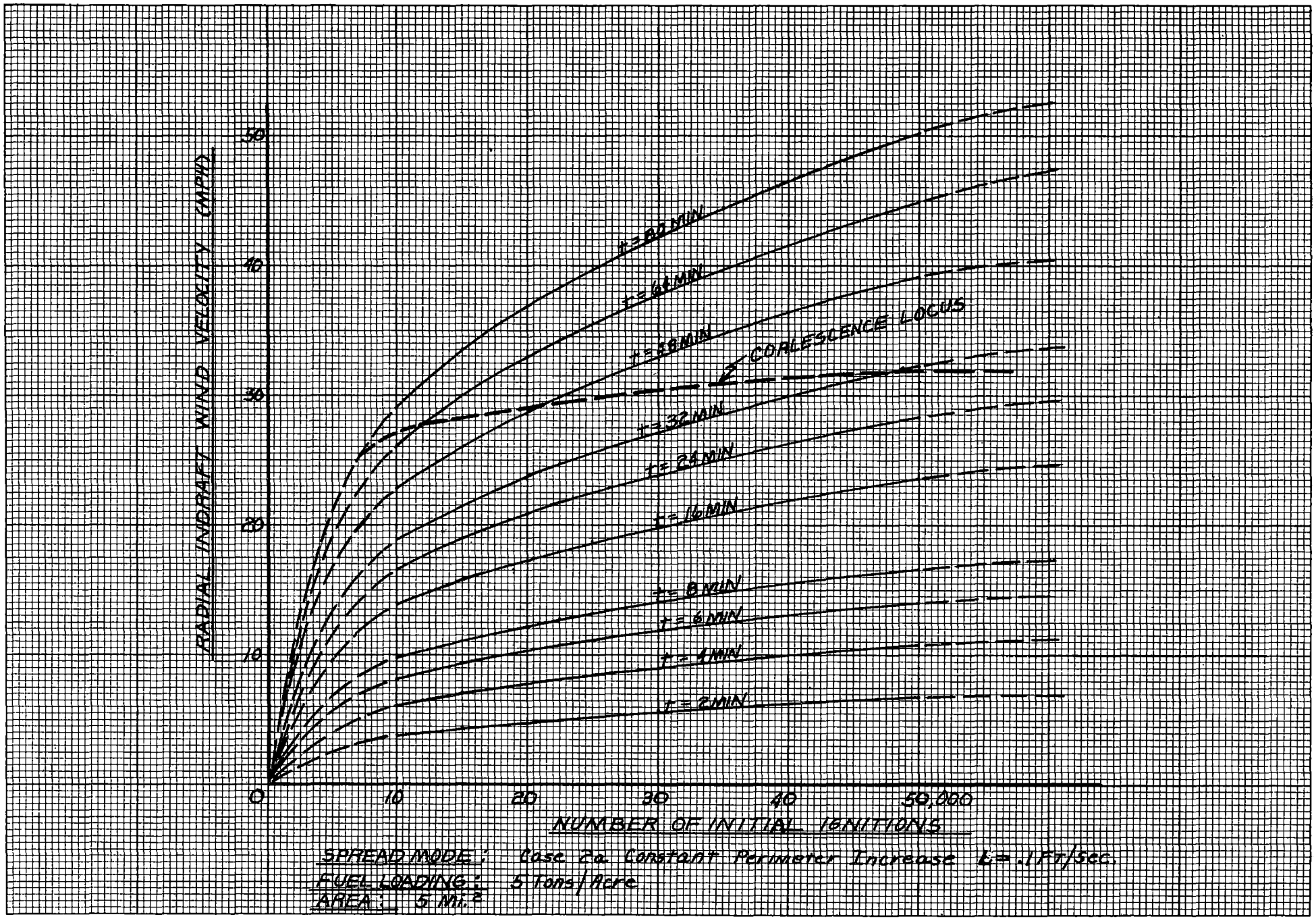
RADIAL INDRAFT WIND VELOCITY (MPH)
50
40
30
20
10
0
10
20
30
40
50,000
NUMBER OF INITIAL IGNITIONS
t = 64 MIN
t = 48 MIN
t = 32 MIN
t = 24 MIN
t = 16 MIN
t = 8 MIN
t = 6 MIN
t = 4 MIN
t = 2 MIN
COALESCENCE LOCUS
SPREAD MODE: Case 2a. Constant Perimeter Increase L = .1 Ft/Sec.
FUEL LOADING: 5 Tons/Acre
AREA: 5 Mi.²

Fig. IV-17

FREDERICK POST COMPANY
301 TR20 CROSS SECTION 20 X 20 PER INCH

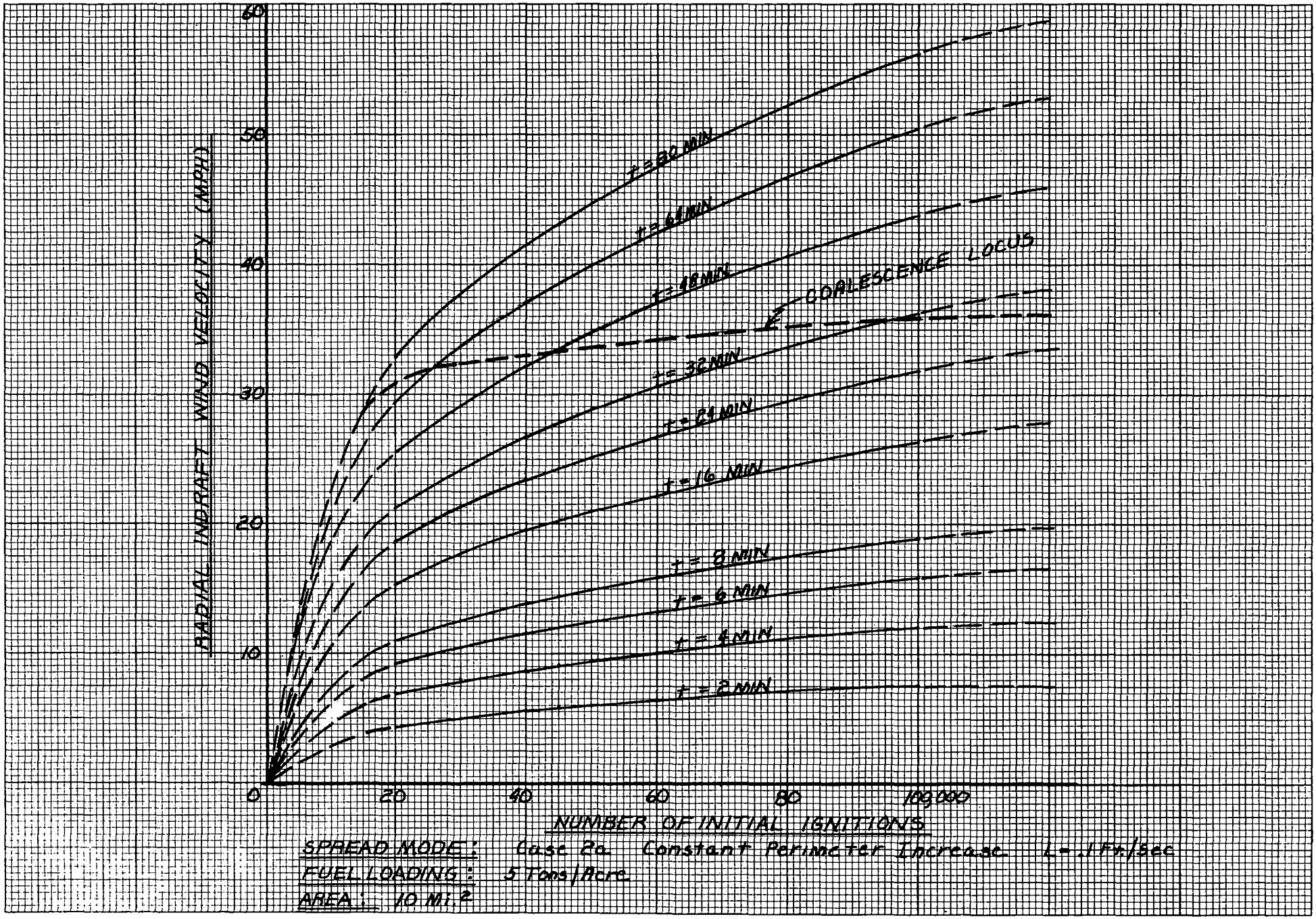

Fig. IV-18

FREDERICK POST COMPANY
301TR20 CROSS SECTION 20 X 20 PER INCH

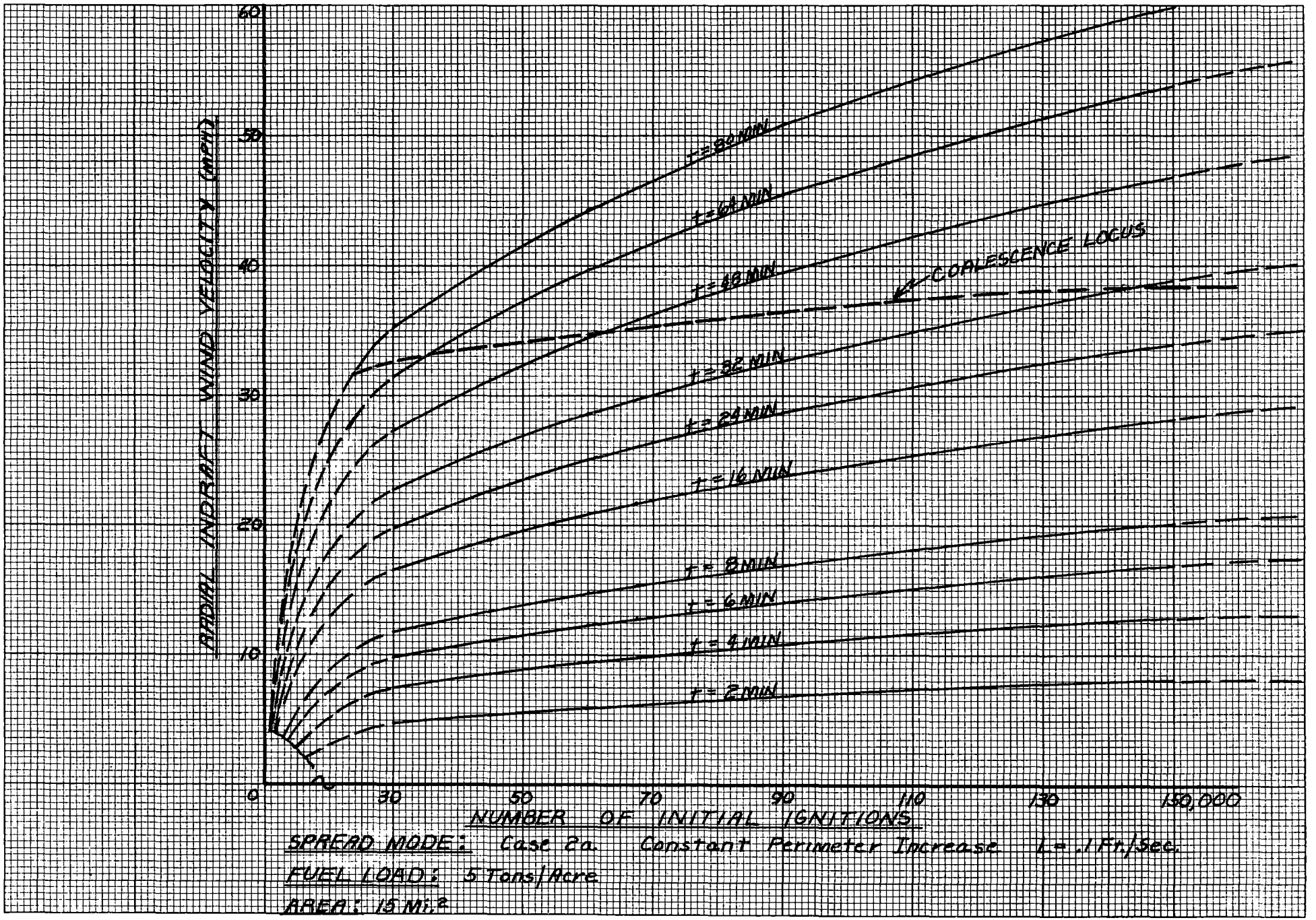

Fig. IV-19

FREDERICK POST COMPANY
301TR20 CROSS SECTION 20 X 20 PER INCH

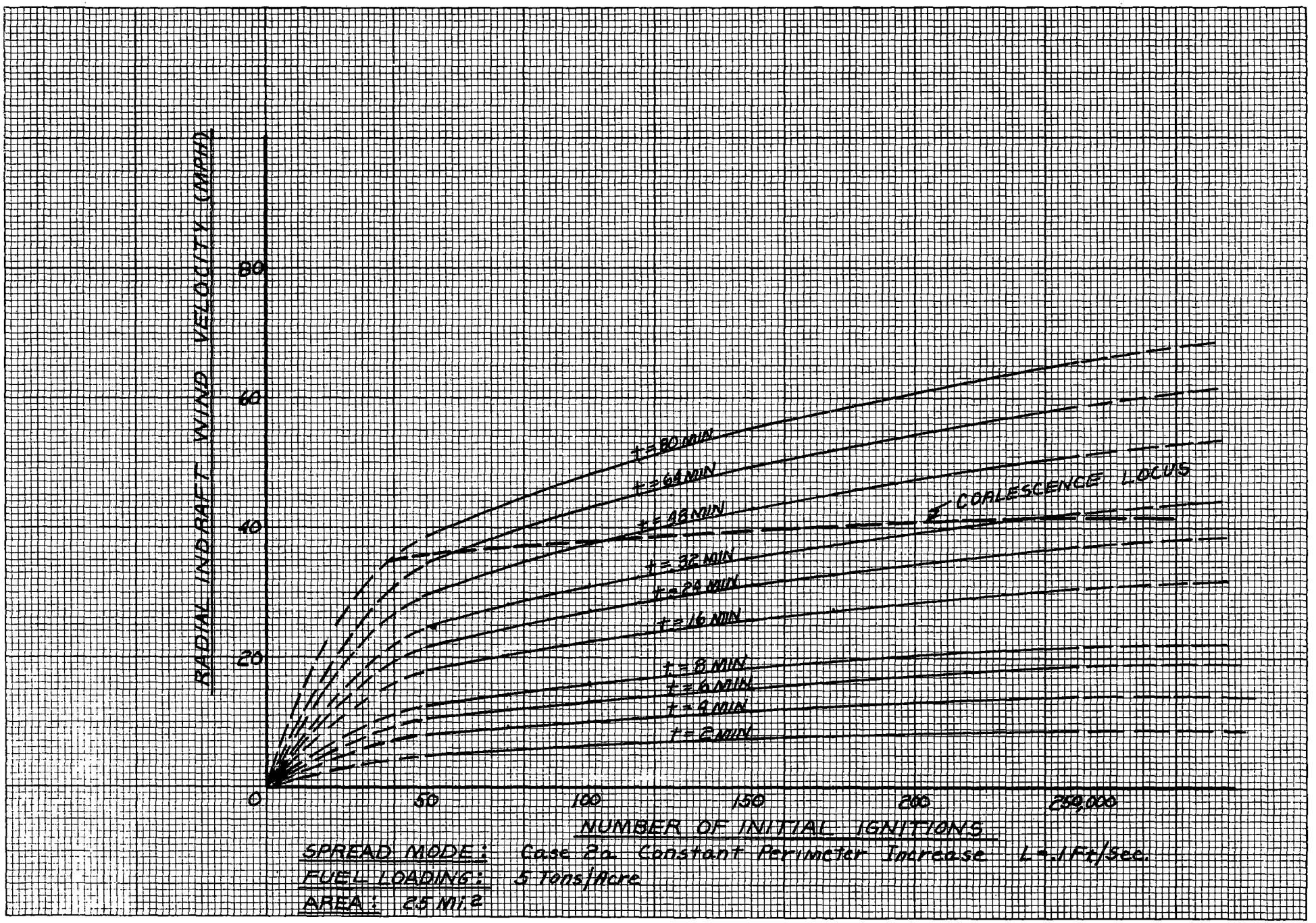

Fig. IV-20

FREDERICK POS. COMPANY
301TR20 CROSS SECTION 20 X 20 PER INCH

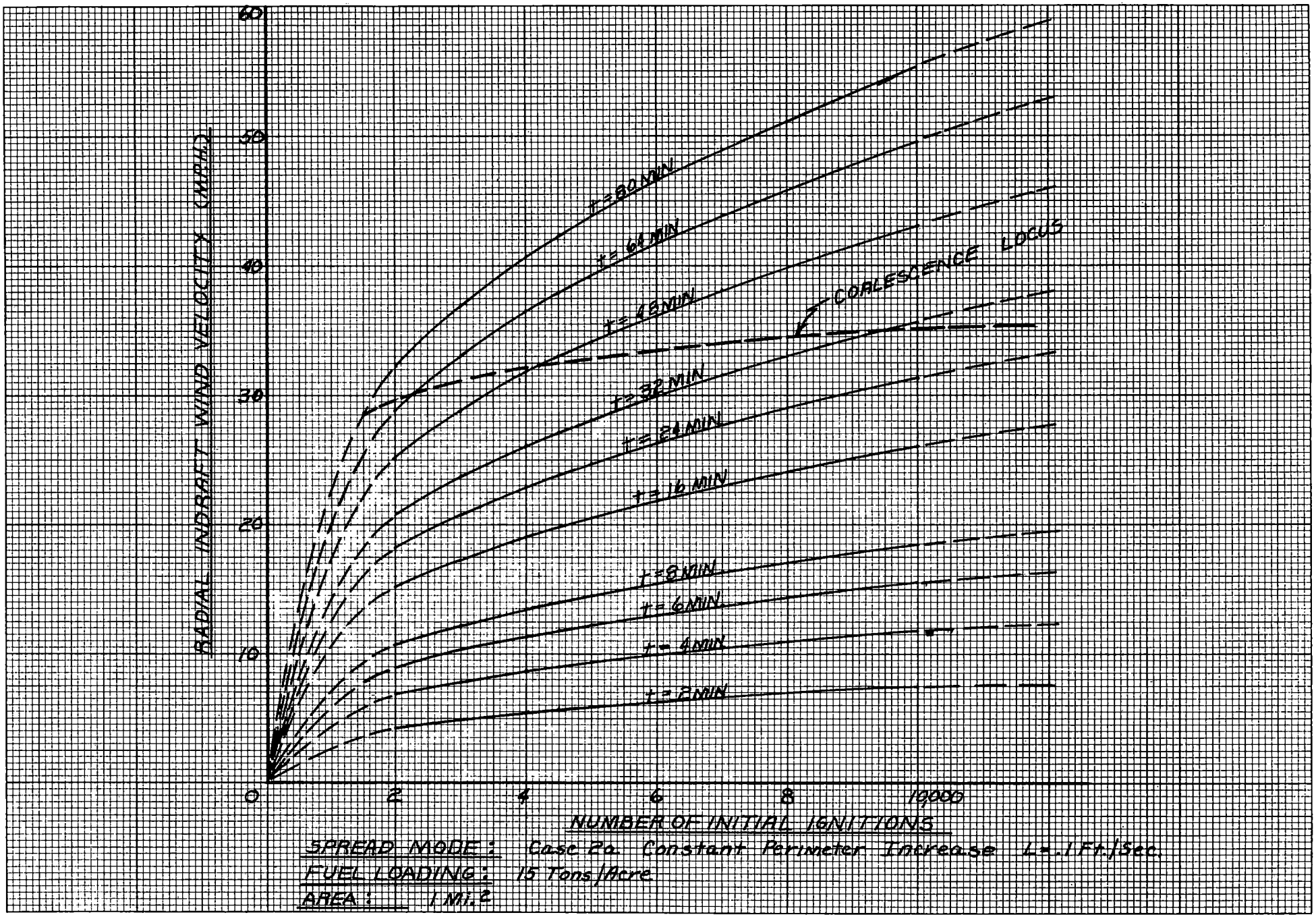

Fig. IV-21

FREDERICK POST COMPANY
301TR20 CROSS SECTION 20 X 20 PER INCH

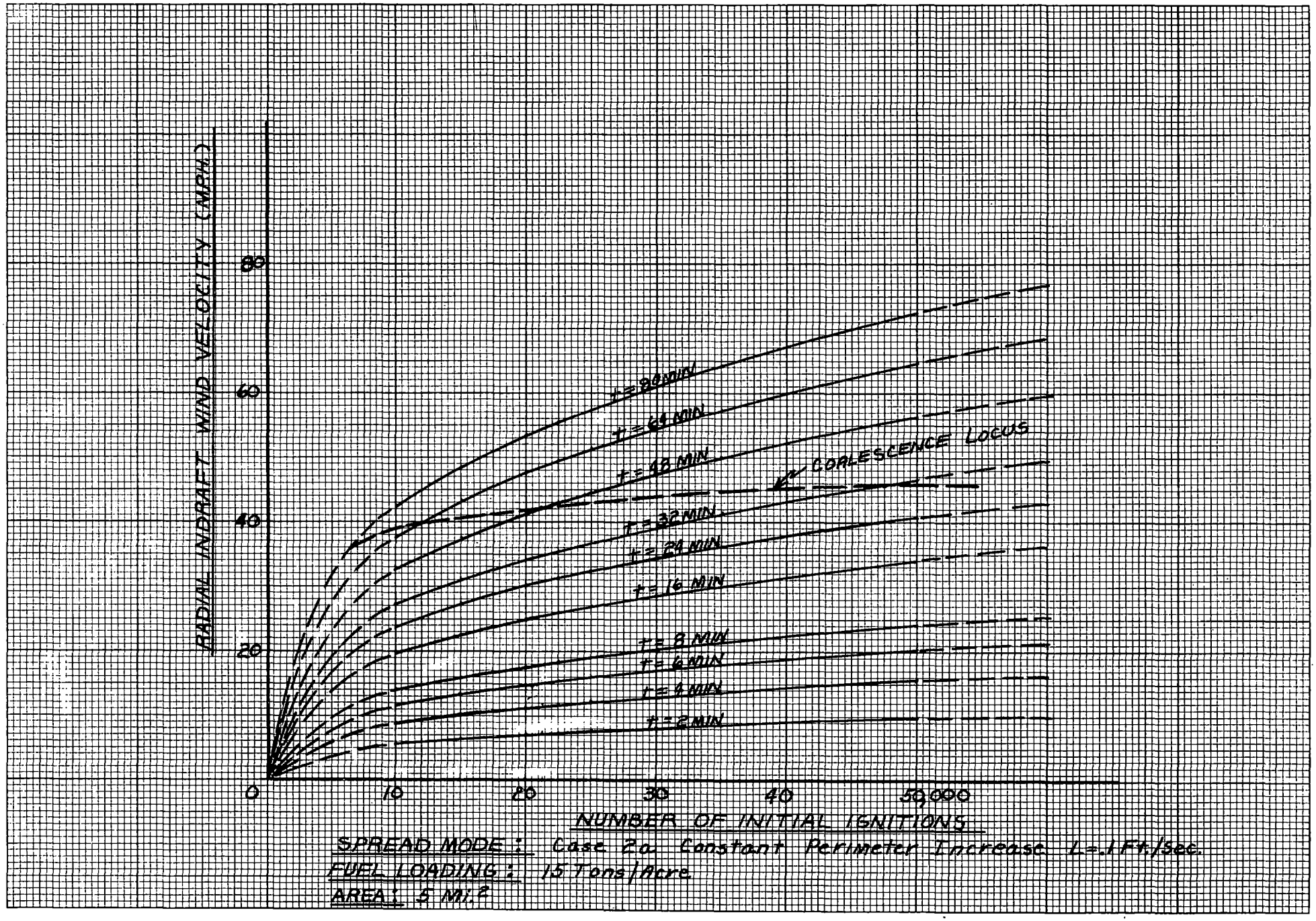

Fig. IV-22

FREDERICK POST COMPANY
301 TR20 CROSS SECTION 20 X 20 PER INCH

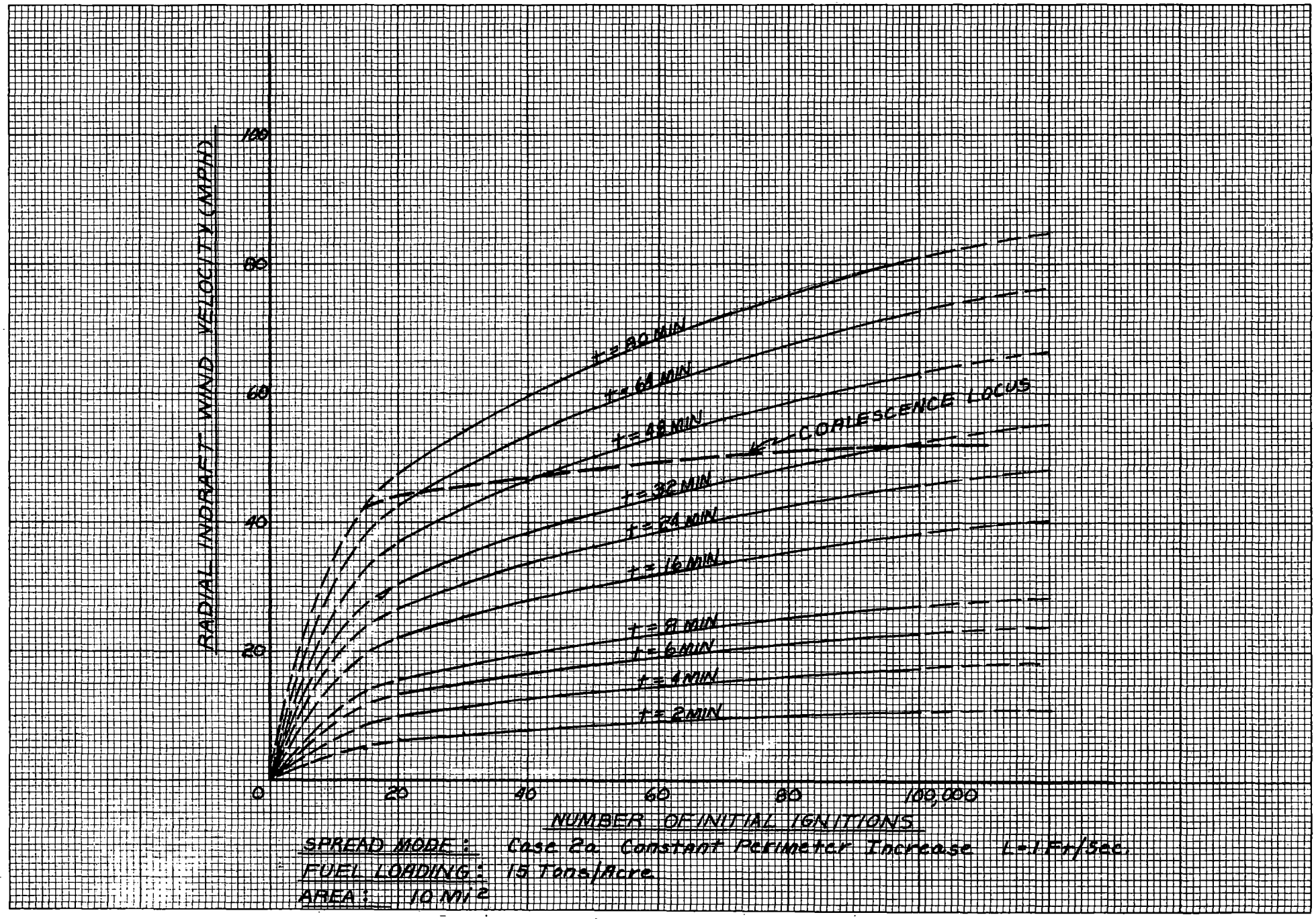

Fig. IV-23

FREDERICK POST COMPANY
301TR20 CROSS SECTION 20 X 20 PER INCH

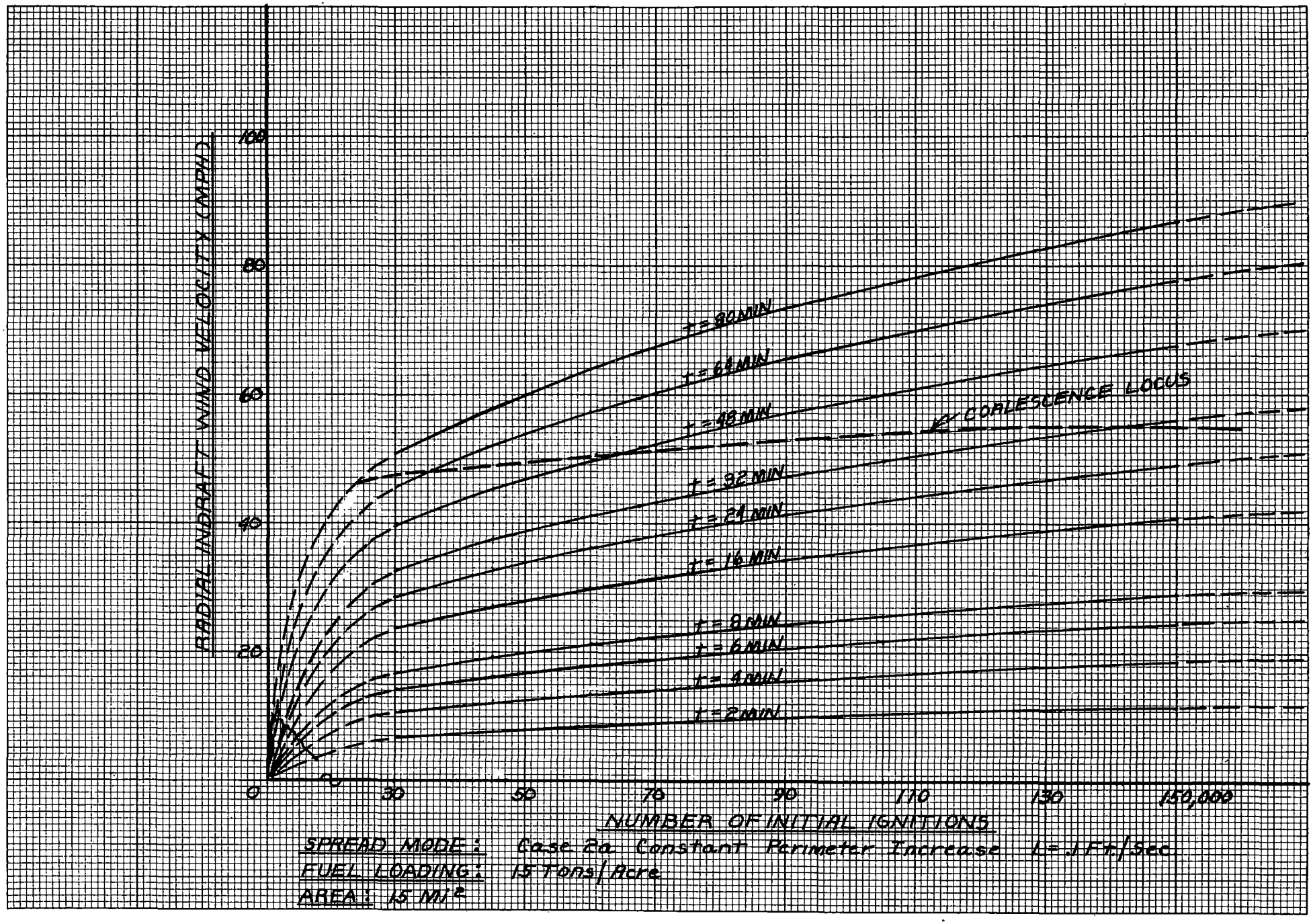

Fig. IV-24

FREDERICK POST COMPANY
301TR20 CROSS SECTION 20 X 20 PER INCH

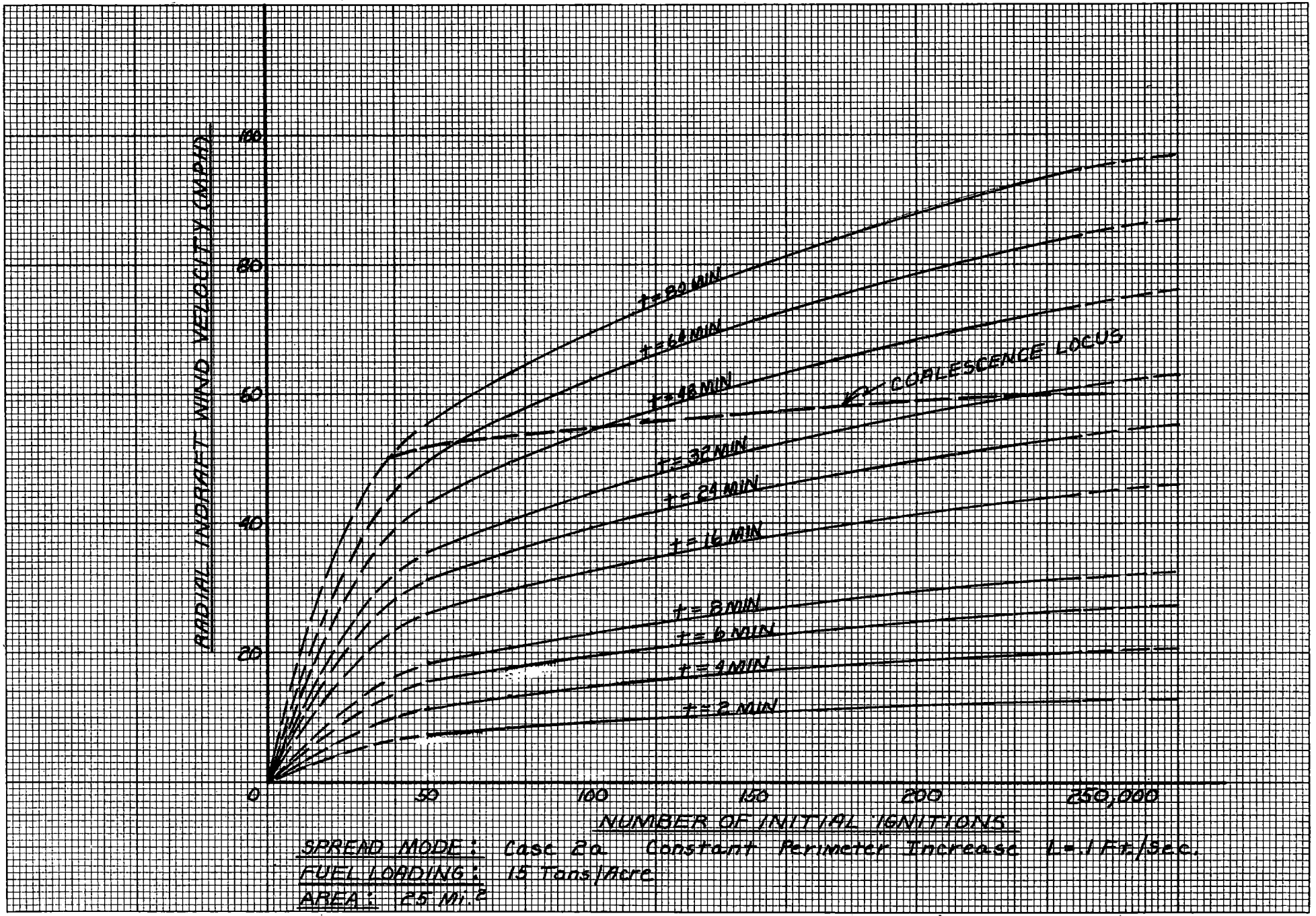

Fig. IV-25

FREDERICK POST COMPANY
30-1 TR20 CROSS SECTION 20 X 20 PER INCH

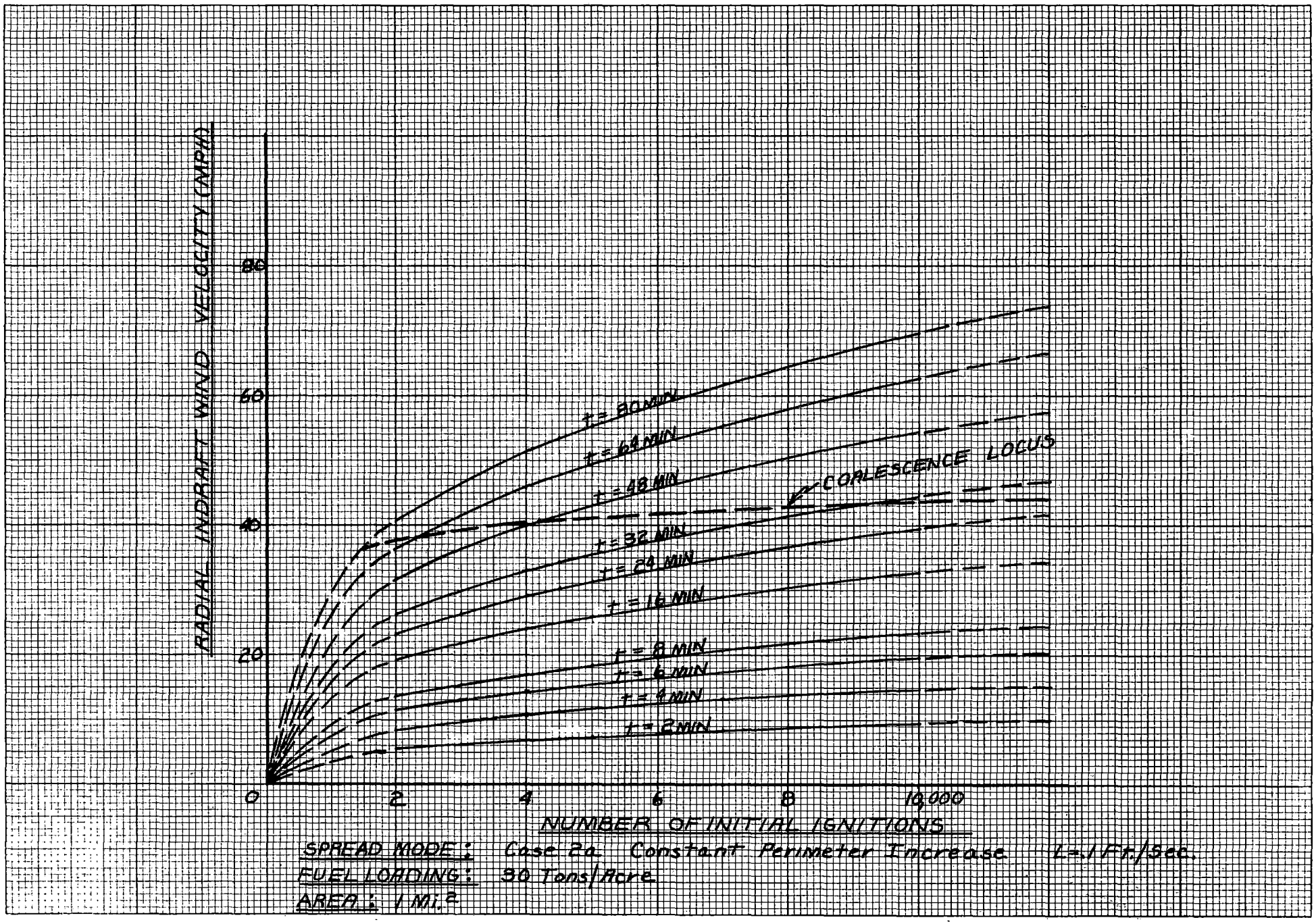

Fig. IV-26

FREDERICK POST COMPANY
301TR20 CROSS SECTION 20 X 20 PER INCH

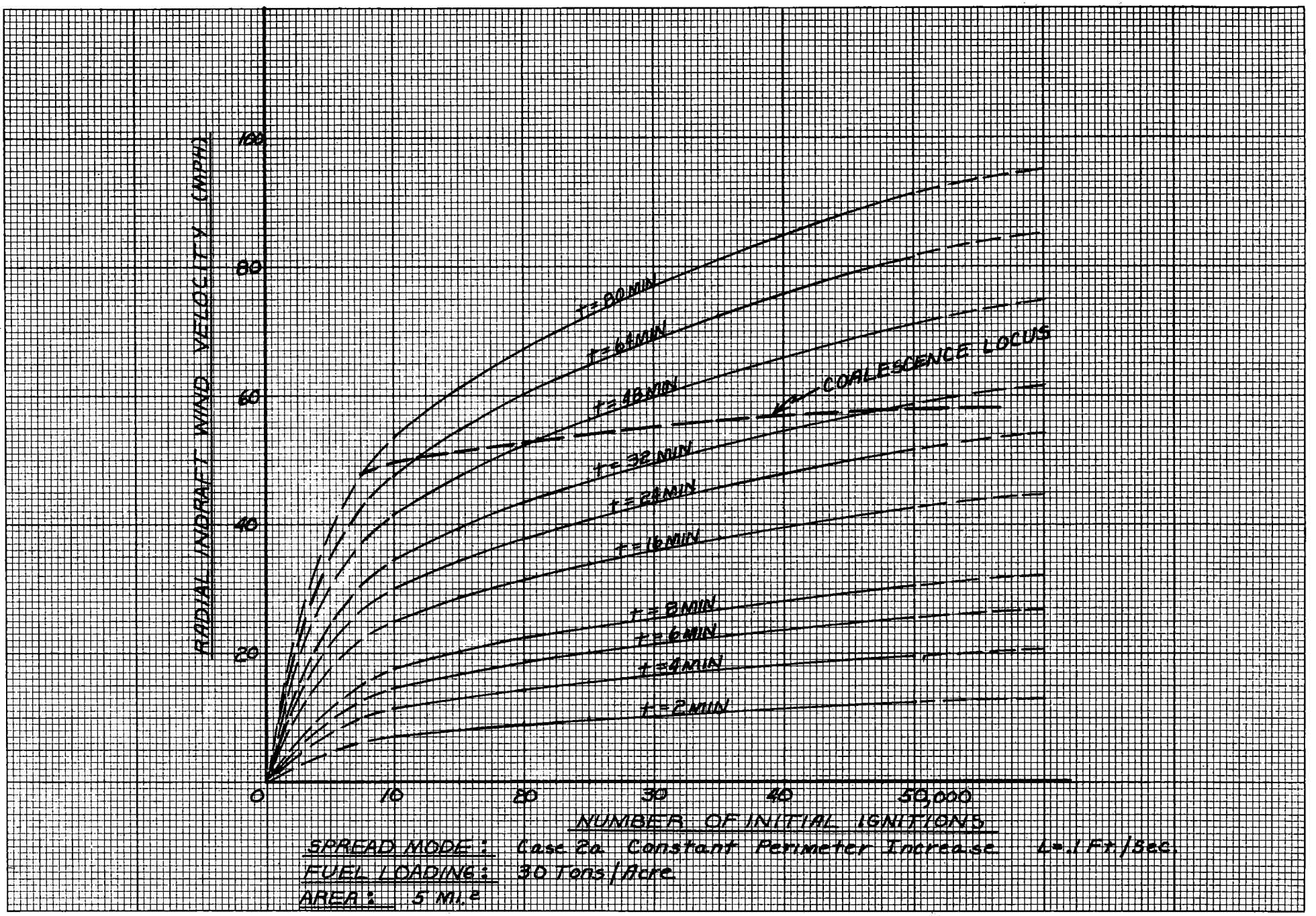

Fig. IV-27

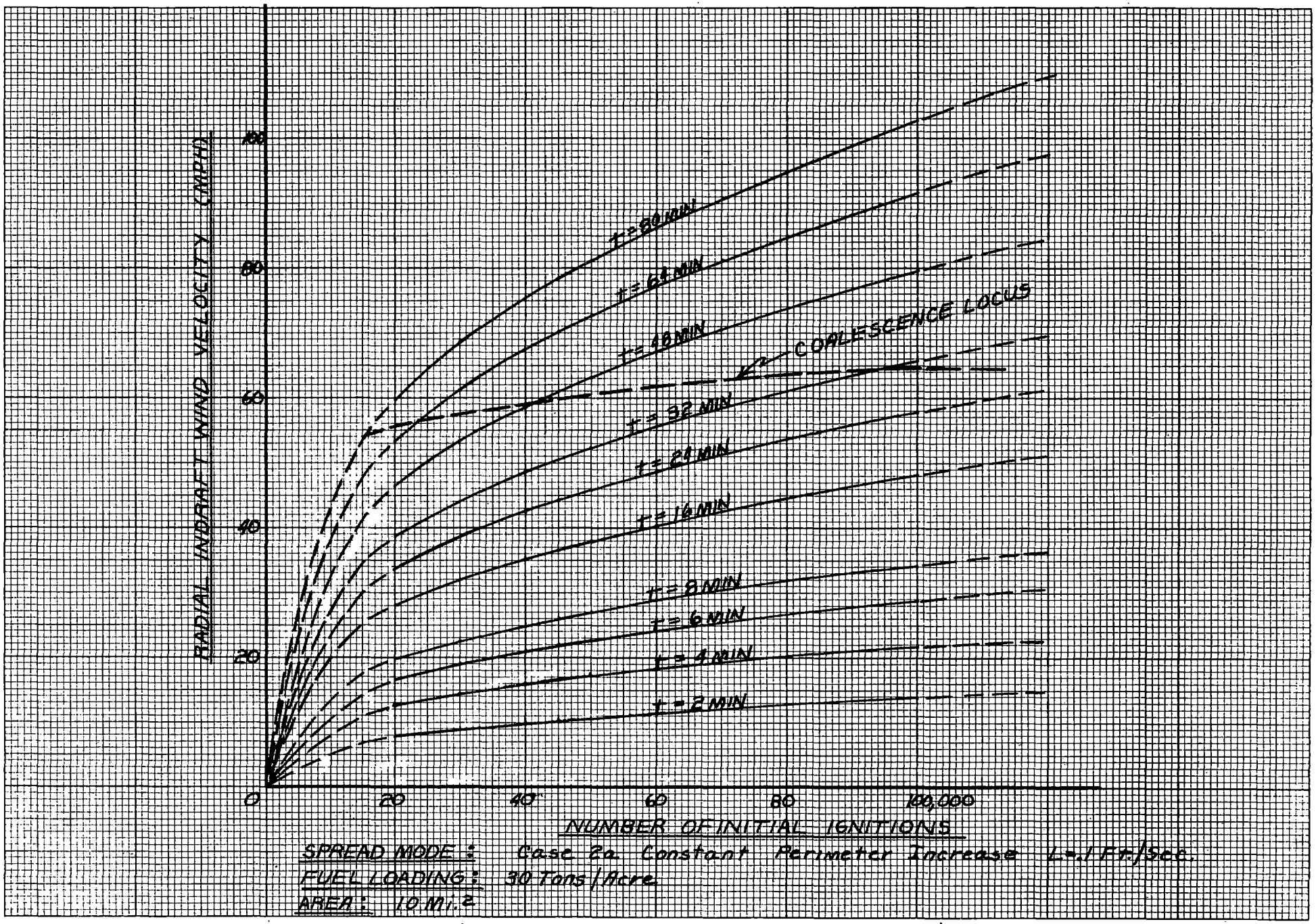
RADIAL INDRAFT WIND VELOCITY (MPH)
100
80
60
40
20
0
20
40
60
80
100,000
NUMBER OF INITIAL IGNITIONS
t = 90 MIN
t = 64 MIN
t = 45 MIN
t = 32 MIN
t = 24 MIN
t = 16 MIN
t = 8 MIN
t = 6 MIN
t = 4 MIN
t = 2 MIN
COALESCENCE LOCUS
SPREAD MODE : Case 2a. Constant Perimeter Increase L=1 Ft./sec.
FUEL LOADING : 30 Tons/Acre
AREA : 10 Mi.2

Fig. IV-28

FREDERICK POST COMPANY
301TR20 CROSS SECTION 20 X 20 PER INCH

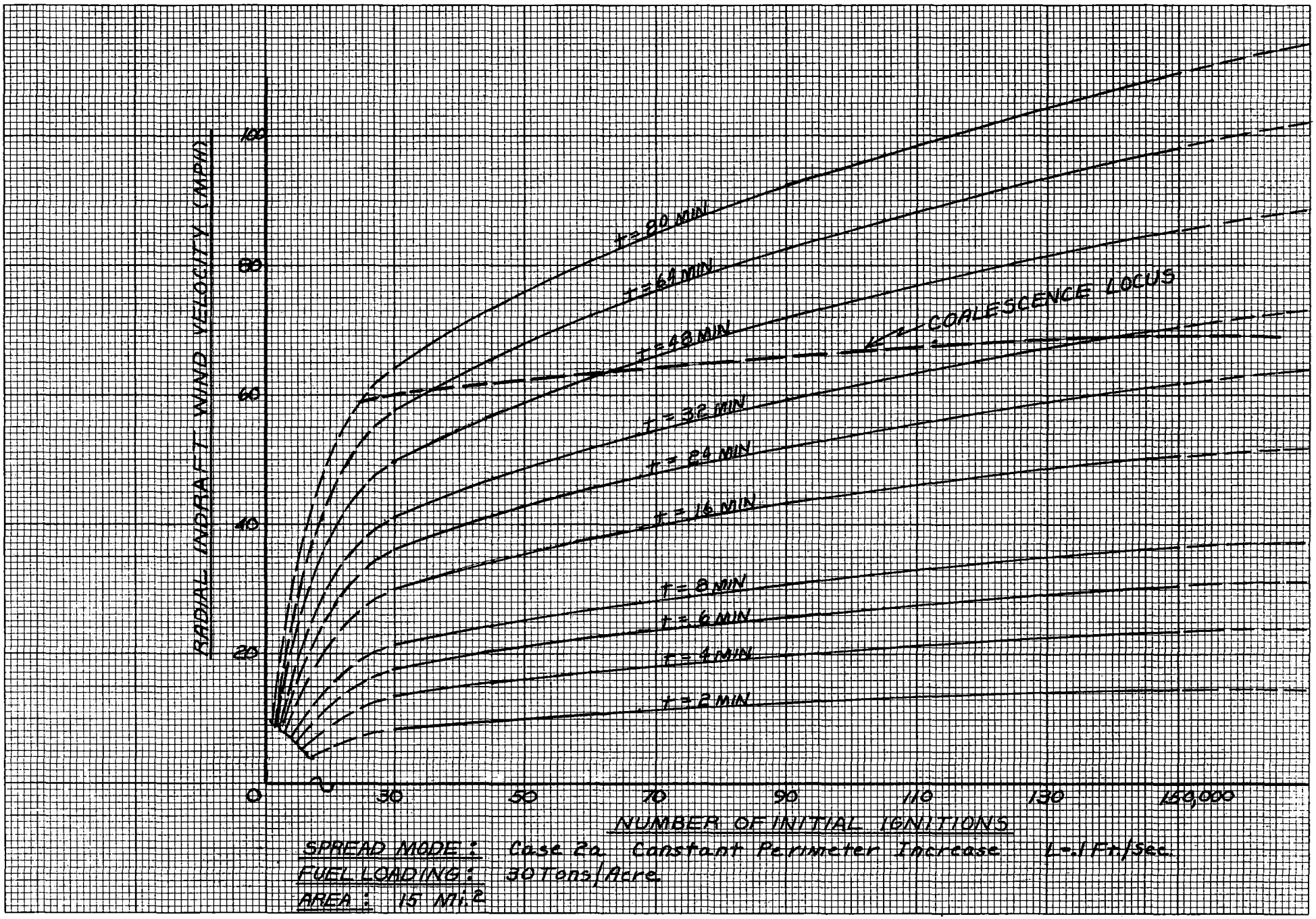

Fig. IV-29

FREDERICK POST COMPANY
301TR20 CROSS SECTION 20 X 20 PER INCH

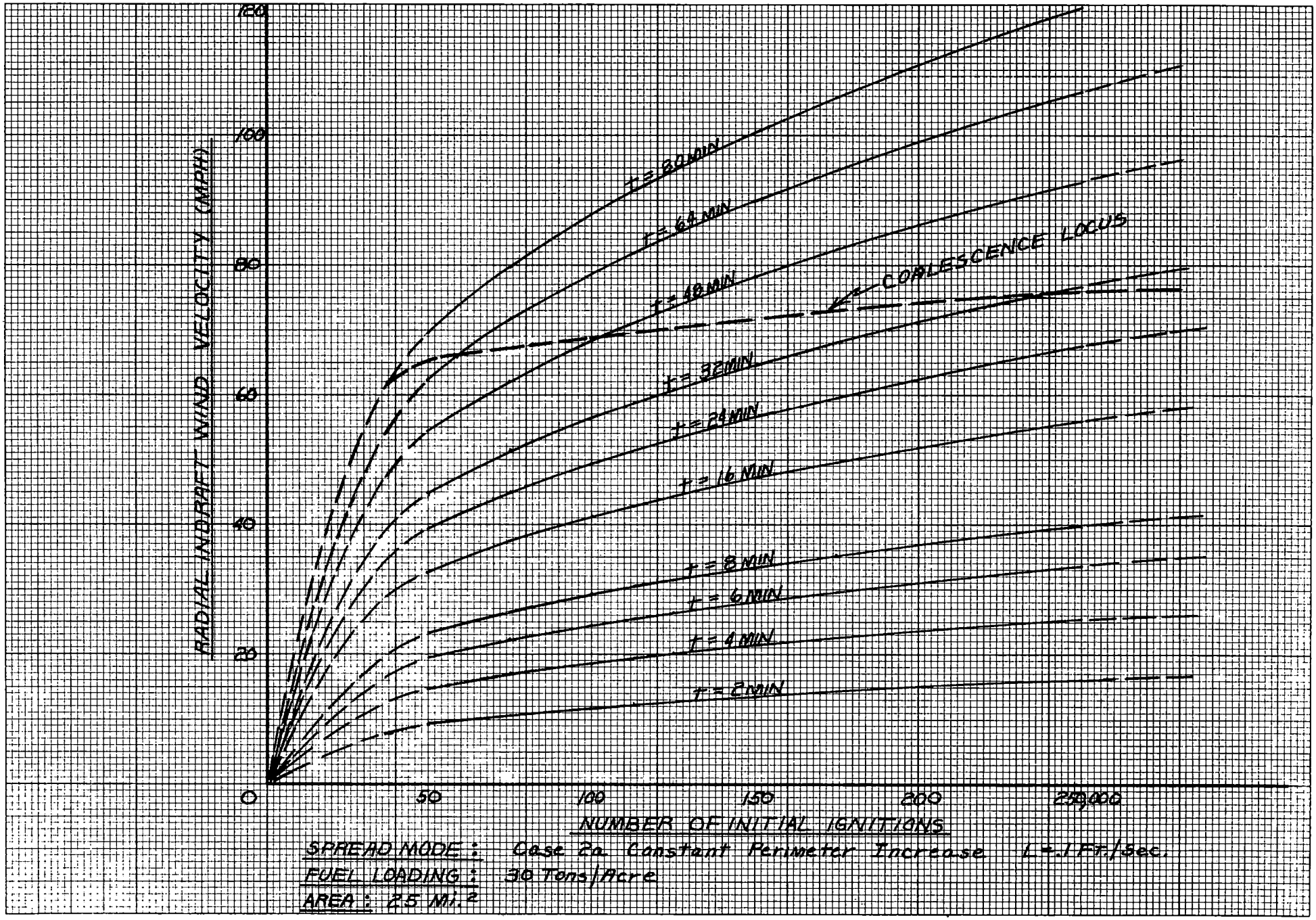

Fig. IV-30

FREDERICK POST COMPANY
301TR20 CROSS SECTION 20 X 20 PER INCH

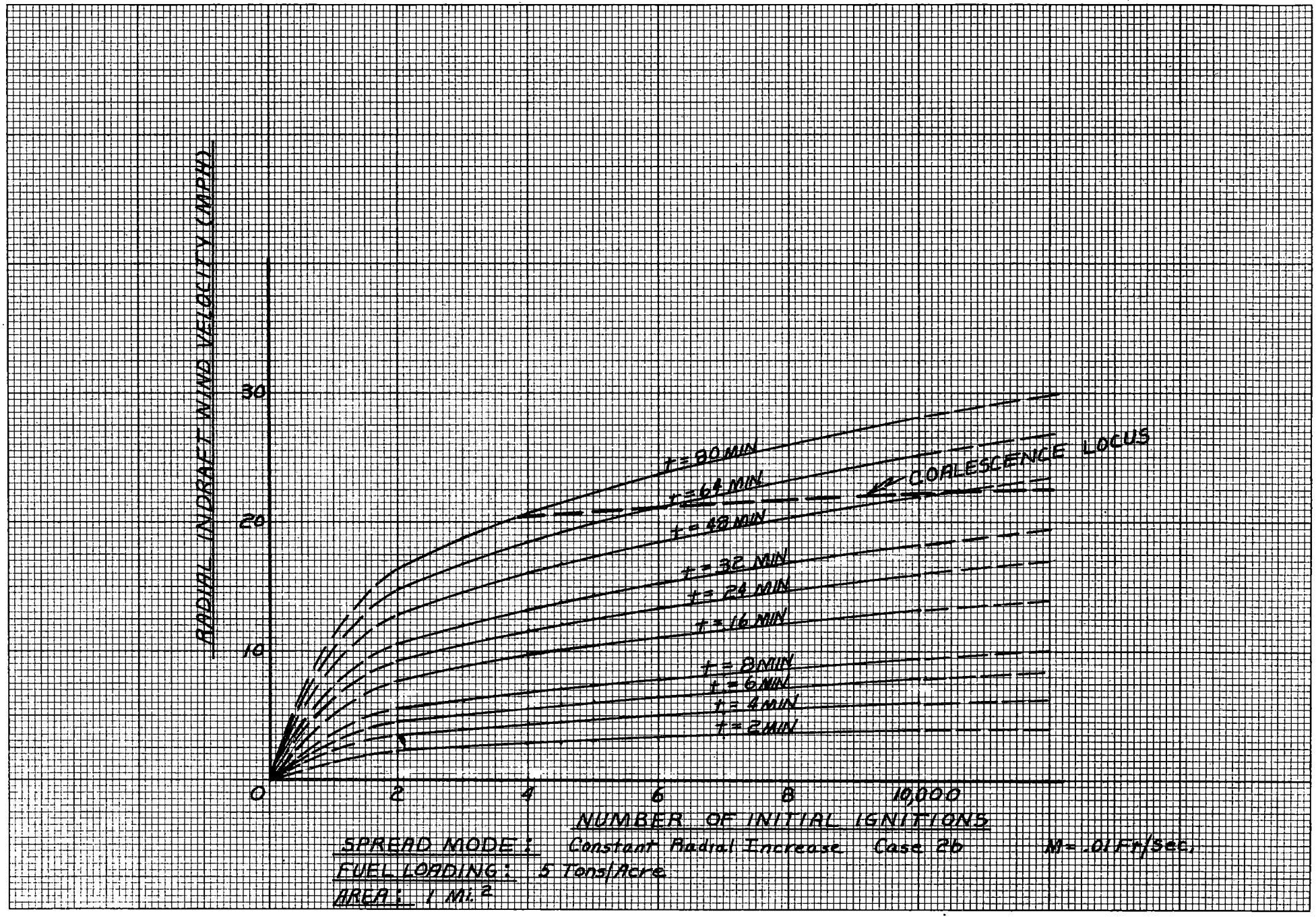

Fig. IV-31

FREDERICK POST COMPANY
301TR20 CROSS SECTION 20 X 20 PER INCH

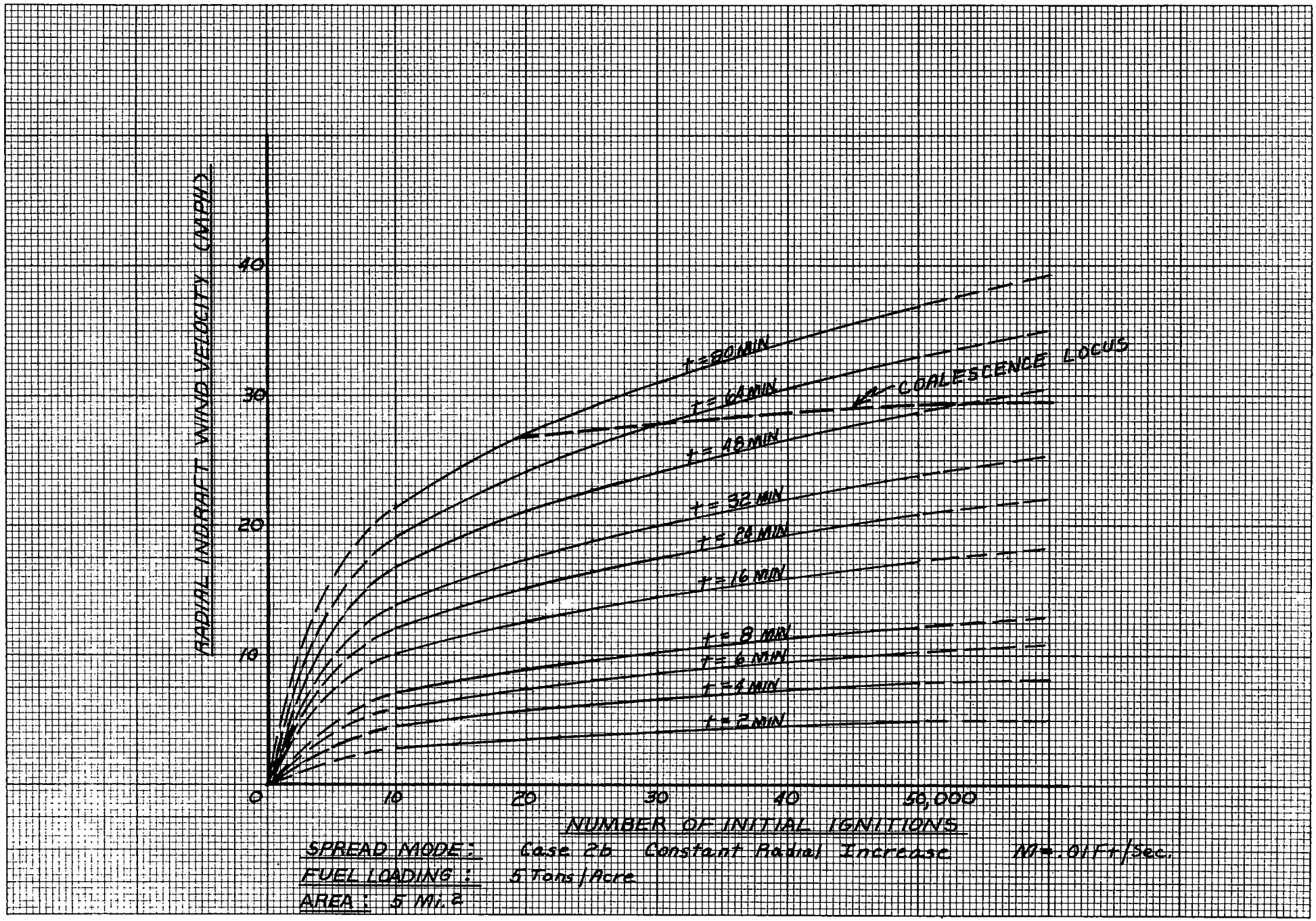

Fig. IV-32

FREDERICK POL. ..PANY
301TR20 CROSS SECTION 20 X 20 PER INCH

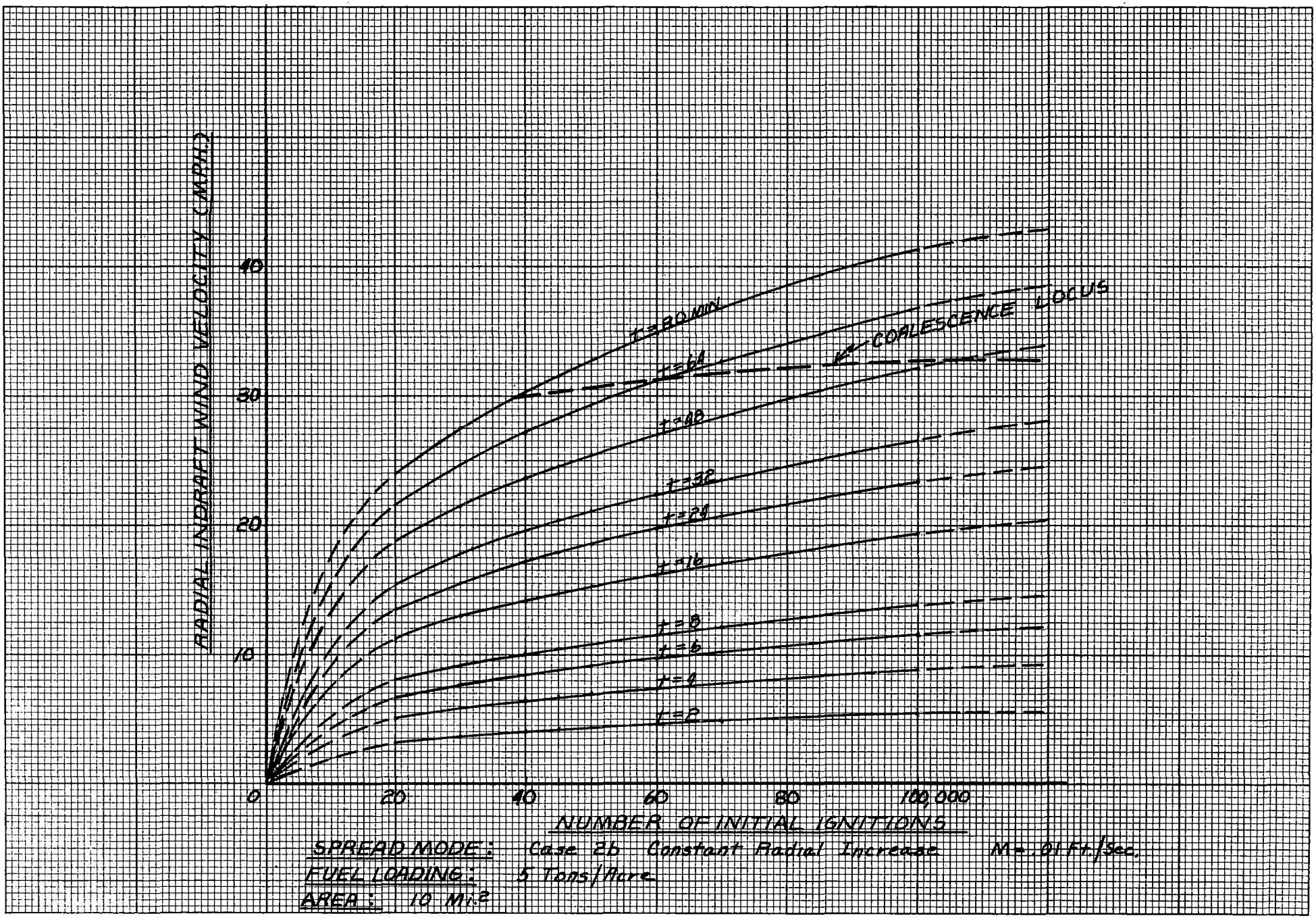

Fig. IV-33

FREDERICK POST COMPANY
301TR20 CROSS SECTION 20 X 20 PER INCH

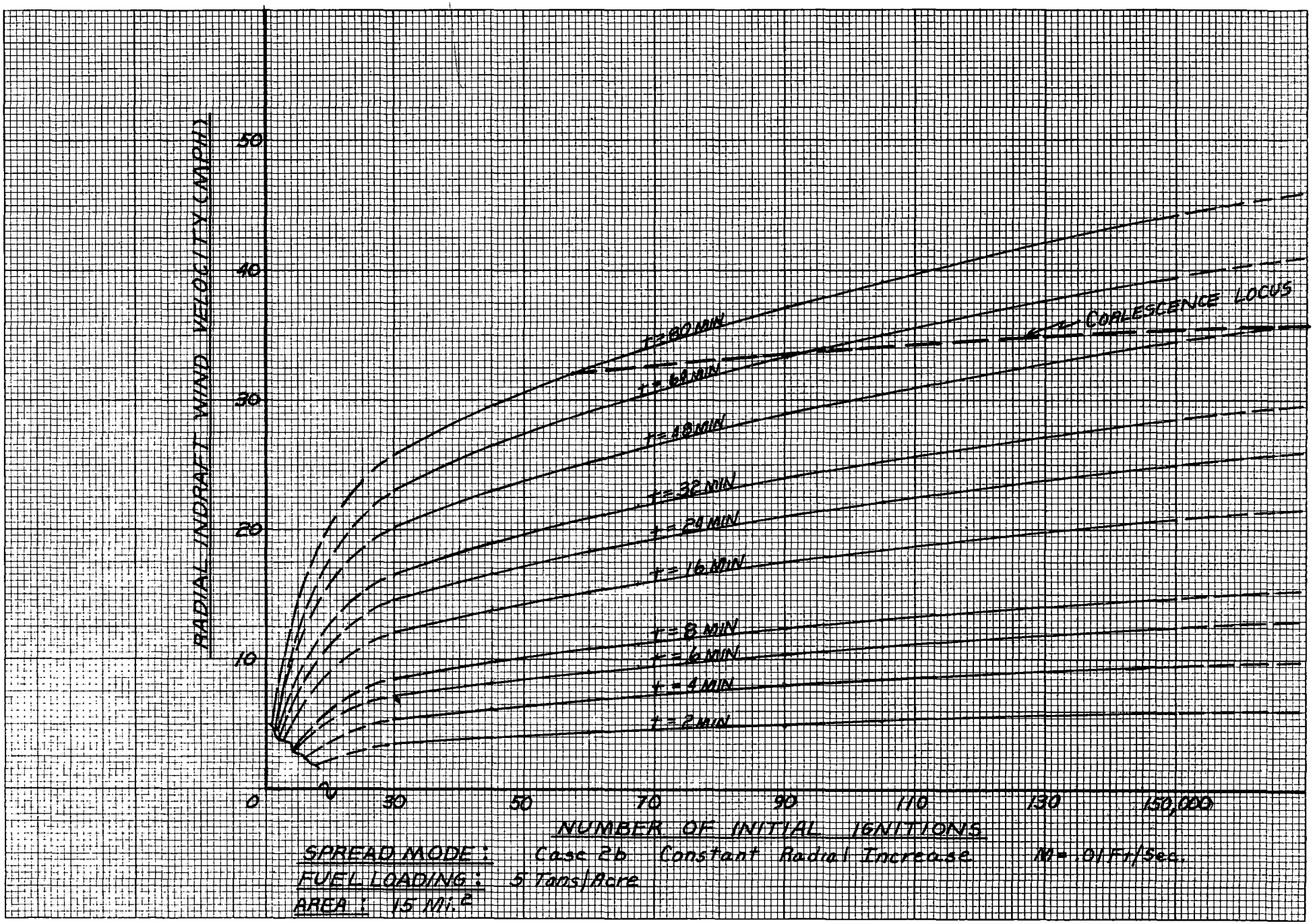

Fig. IV-34

FREDERICK POST COMPANY
301TR20 CROSS SECTION 20 X 20 PER INCH

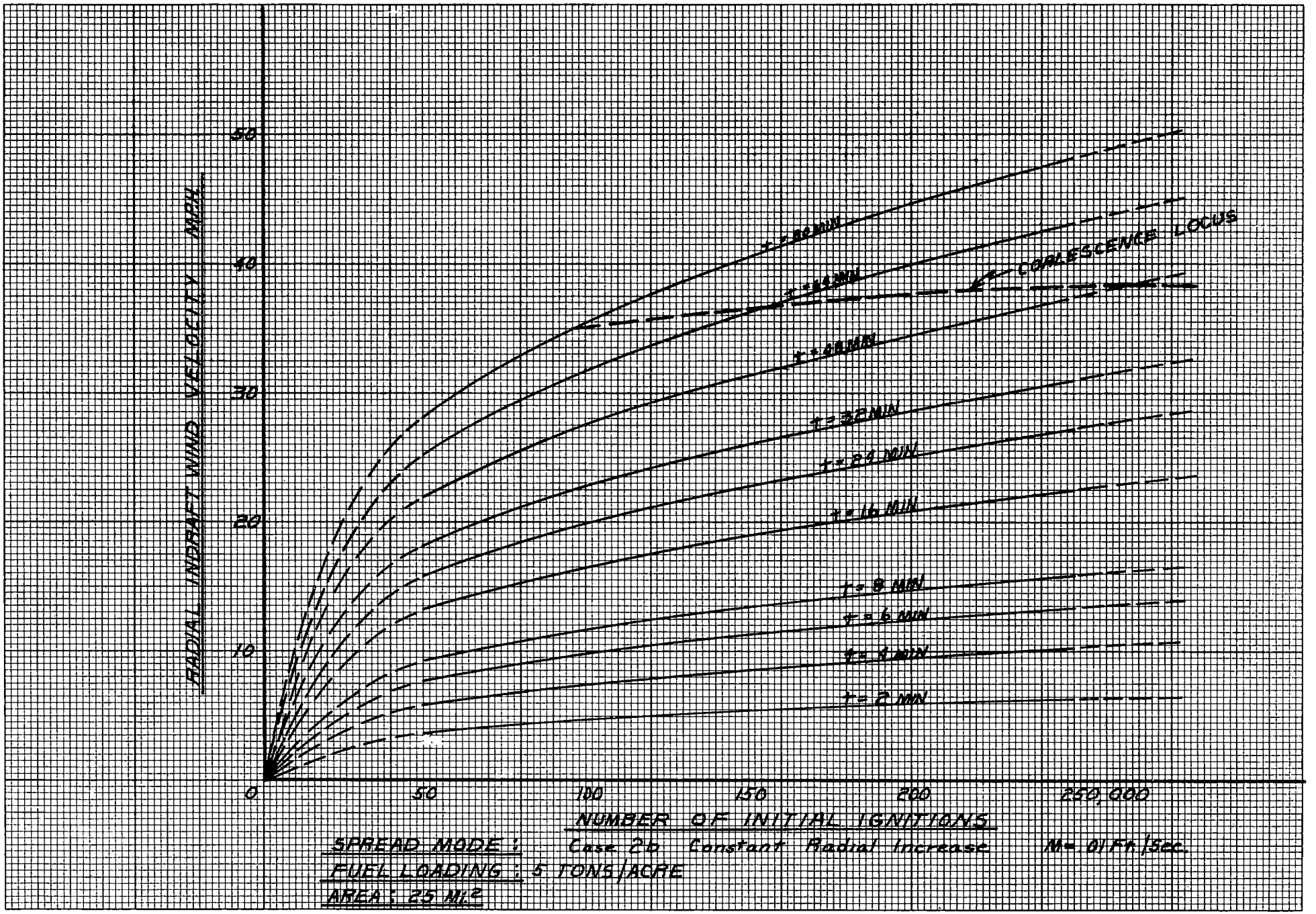

Fig. IV-35

FREDERICK POST COMPANY
301TR20 CROSS SECTION 20 X 20 PER INCH

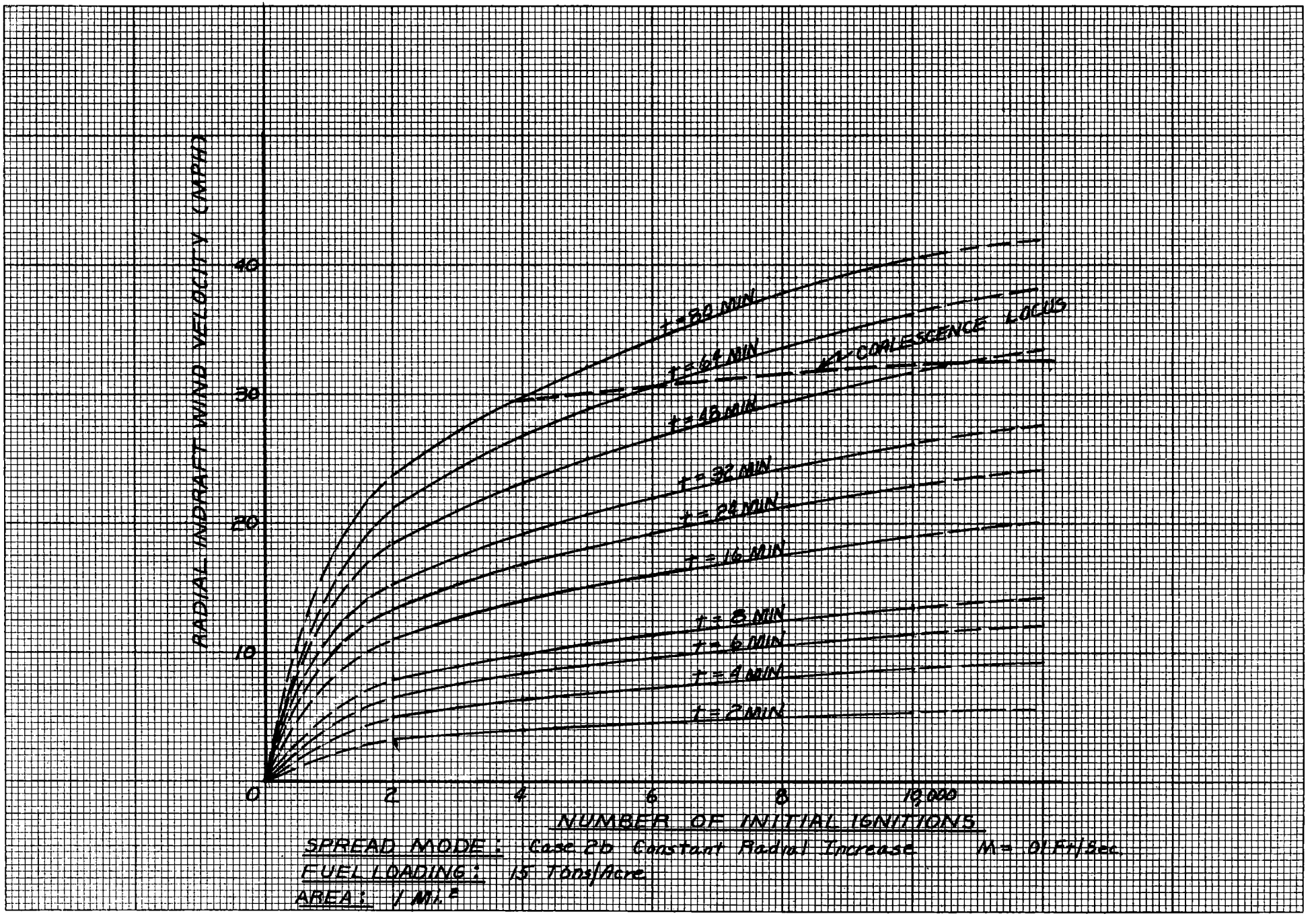

Fig. IV-36

FREDERICK POST COMPANY
301TR20 CROSS SECTION 20 X 20 PER INCH

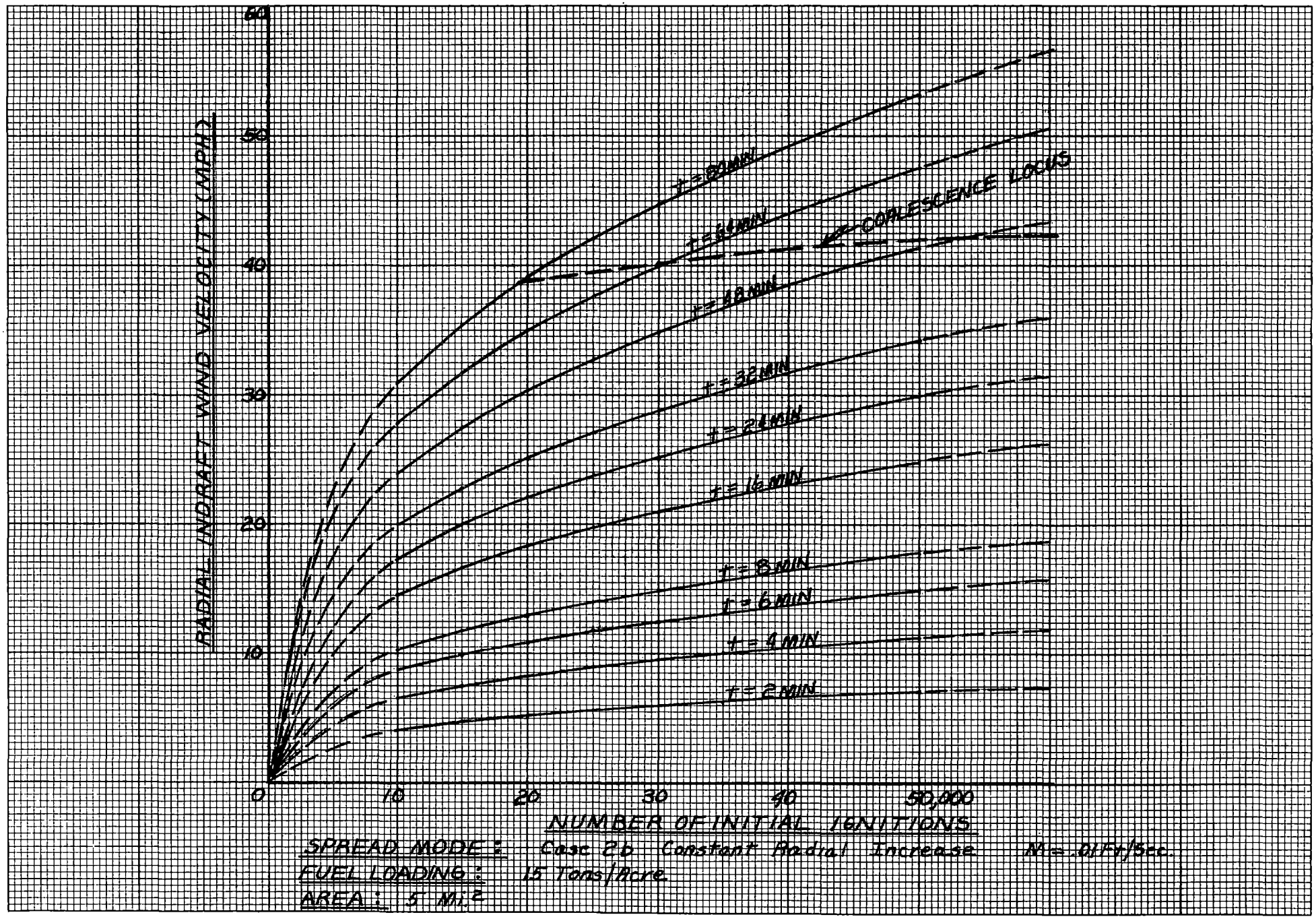

Fig. IV-37

FREDERICK POST COMPANY
301 TR20 CROSS SECTION 20 X 20 PER INCH

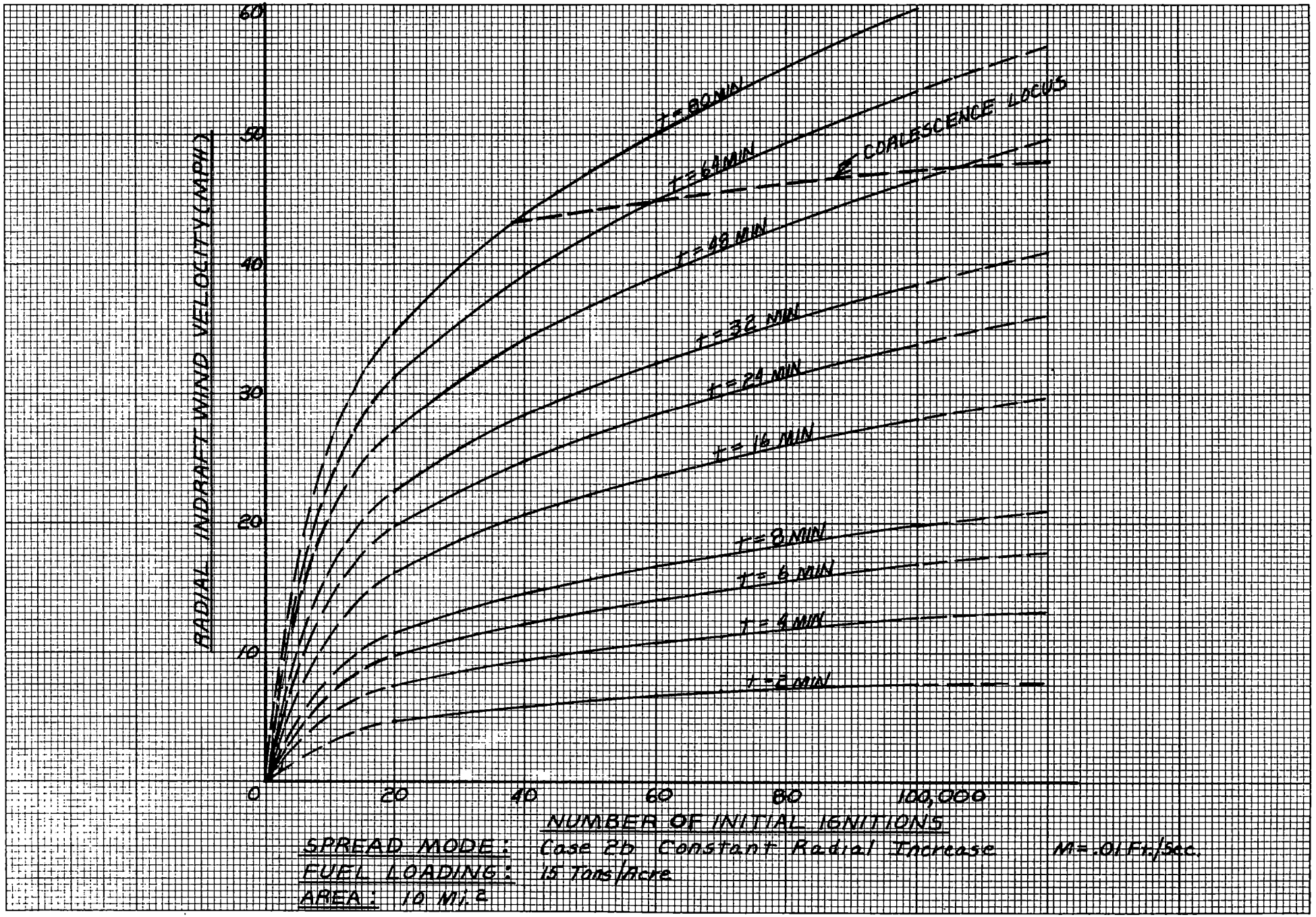

Fig. IV-38

FREDERICK POST COMPANY
301TR20 CROSS SECTION 20 X 20 PER INCH

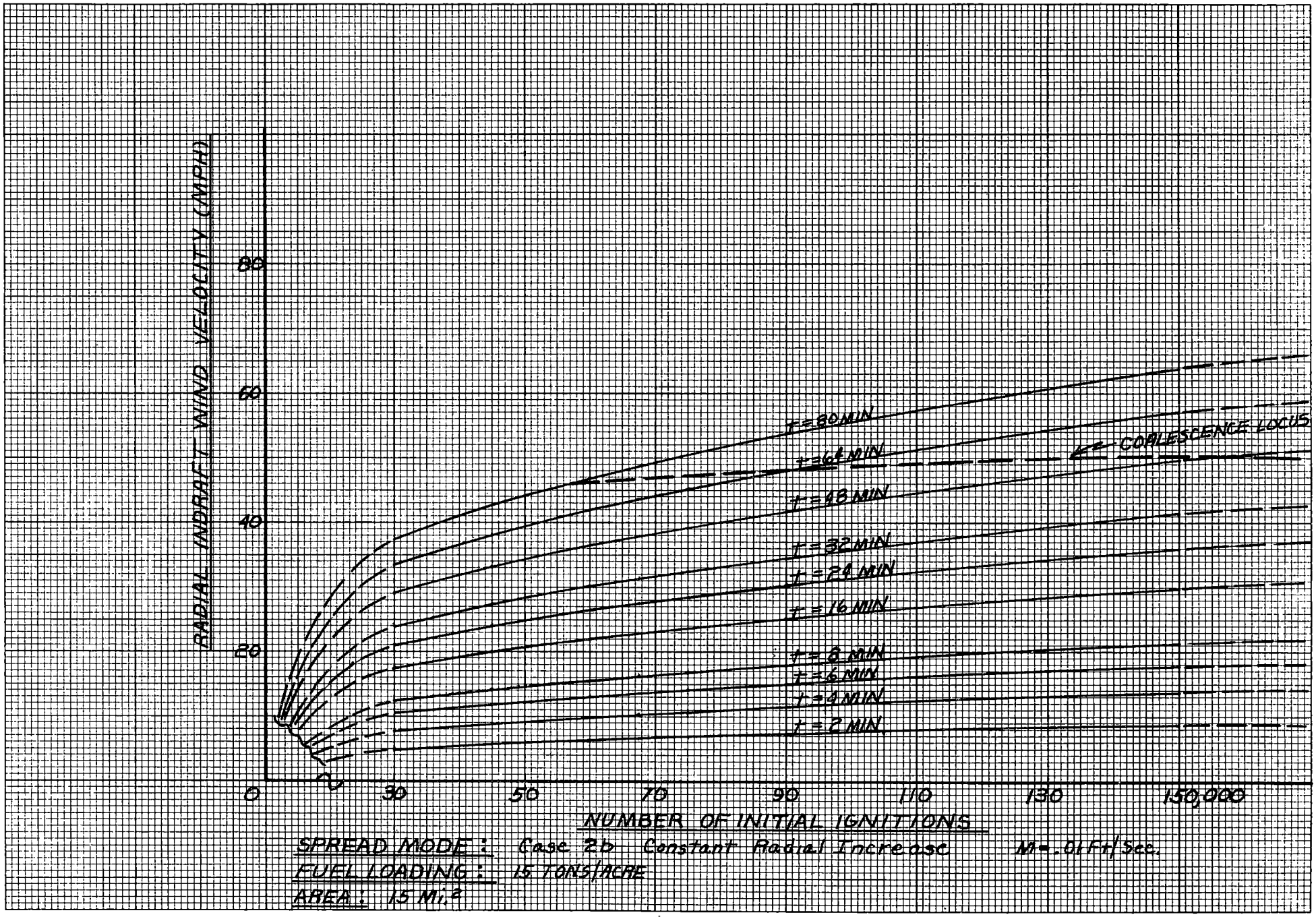

Fig. IV-39

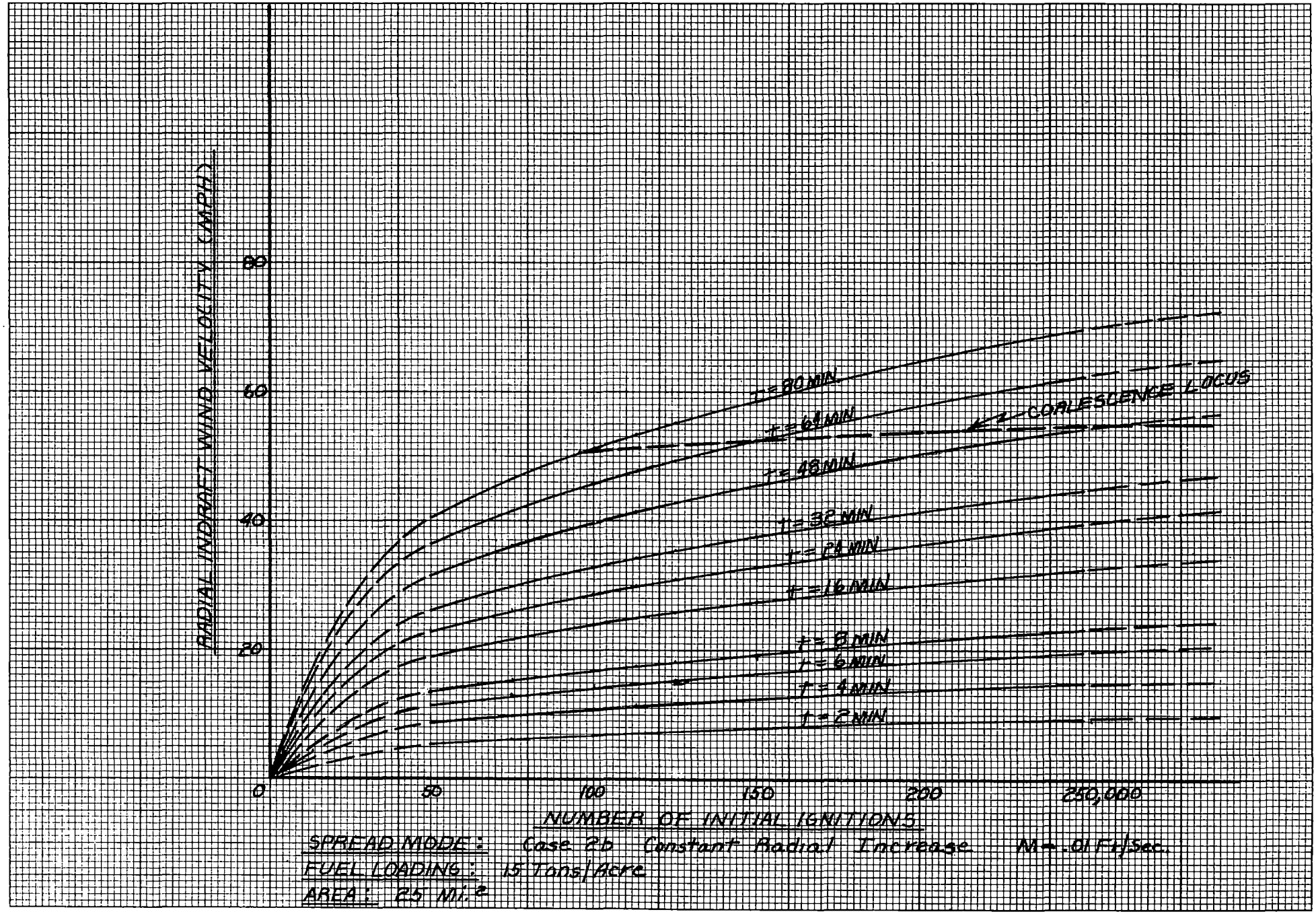
RADIAL INDRAFT WIND VELOCITY (MPH)
80
60
40
20
0
50
100
150
200
250,000
NUMBER OF INITIAL IGNITIONS
t = 80 MIN
t = 64 MIN
t = 48 MIN
t = 32 MIN
t = 24 MIN
t = 16 MIN
t = 8 MIN
t = 6 MIN
t = 4 MIN
t = 2 MIN
COALESCENCE LOCUS
SPREAD MODE: Case 2b Constant Radial Increase M = .01 Ft/Sec.
FUEL LOADING: 15 Tons/Acre
AREA: 25 Mi.²

Fig. IV-40

FREDERICK POST COMPANY
301TR20 CROSS SECTION 20 X 20 PER INCH

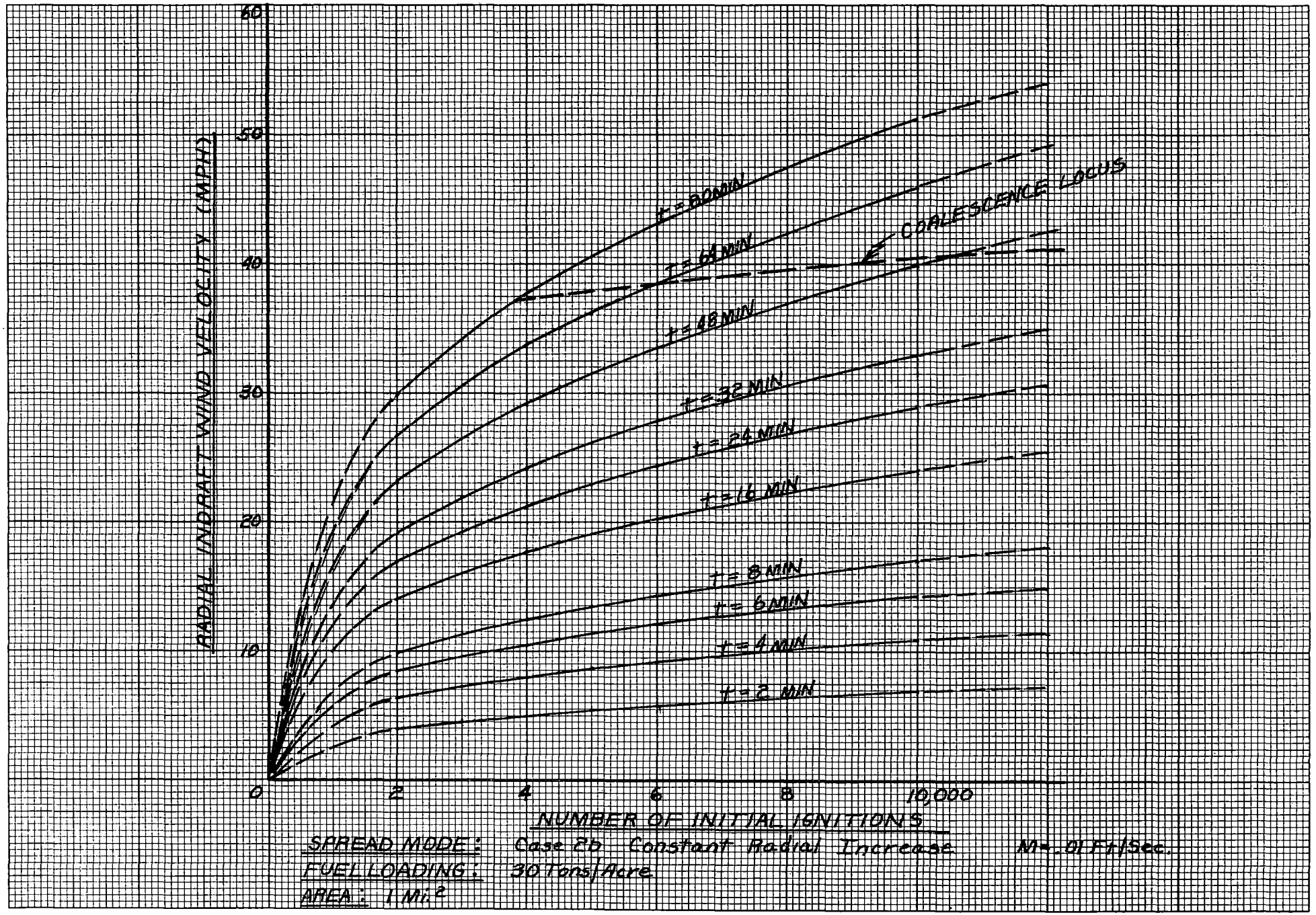

Fig. IV-41

FREDERICK POST COMPANY
301TR20 CROSS SECTION 20 X 20 PER INCH

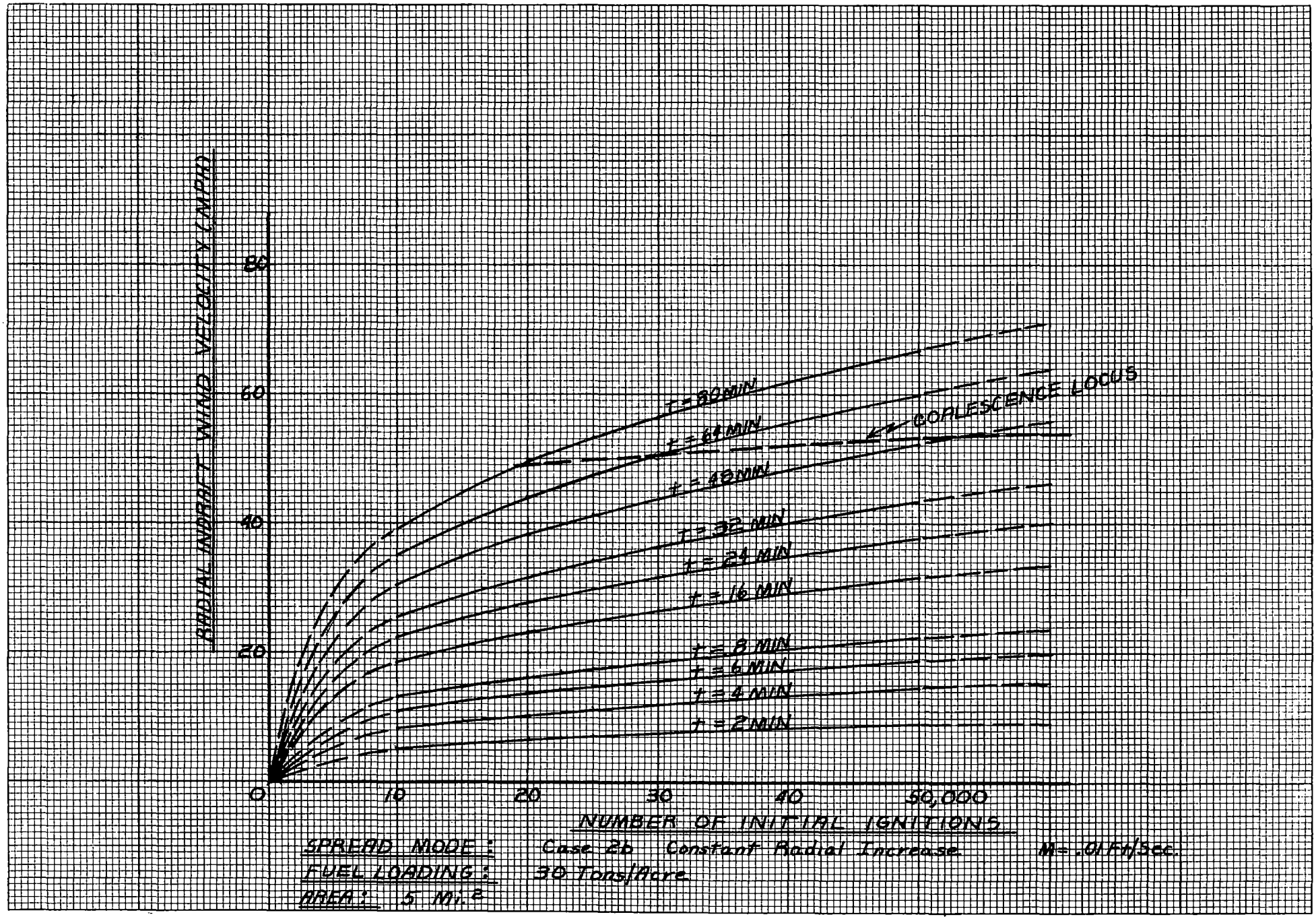

Fig. IV-42

FREDERICK POST COMPANY
301TR20 CROSS SECTION 20 X 20 PER INCH

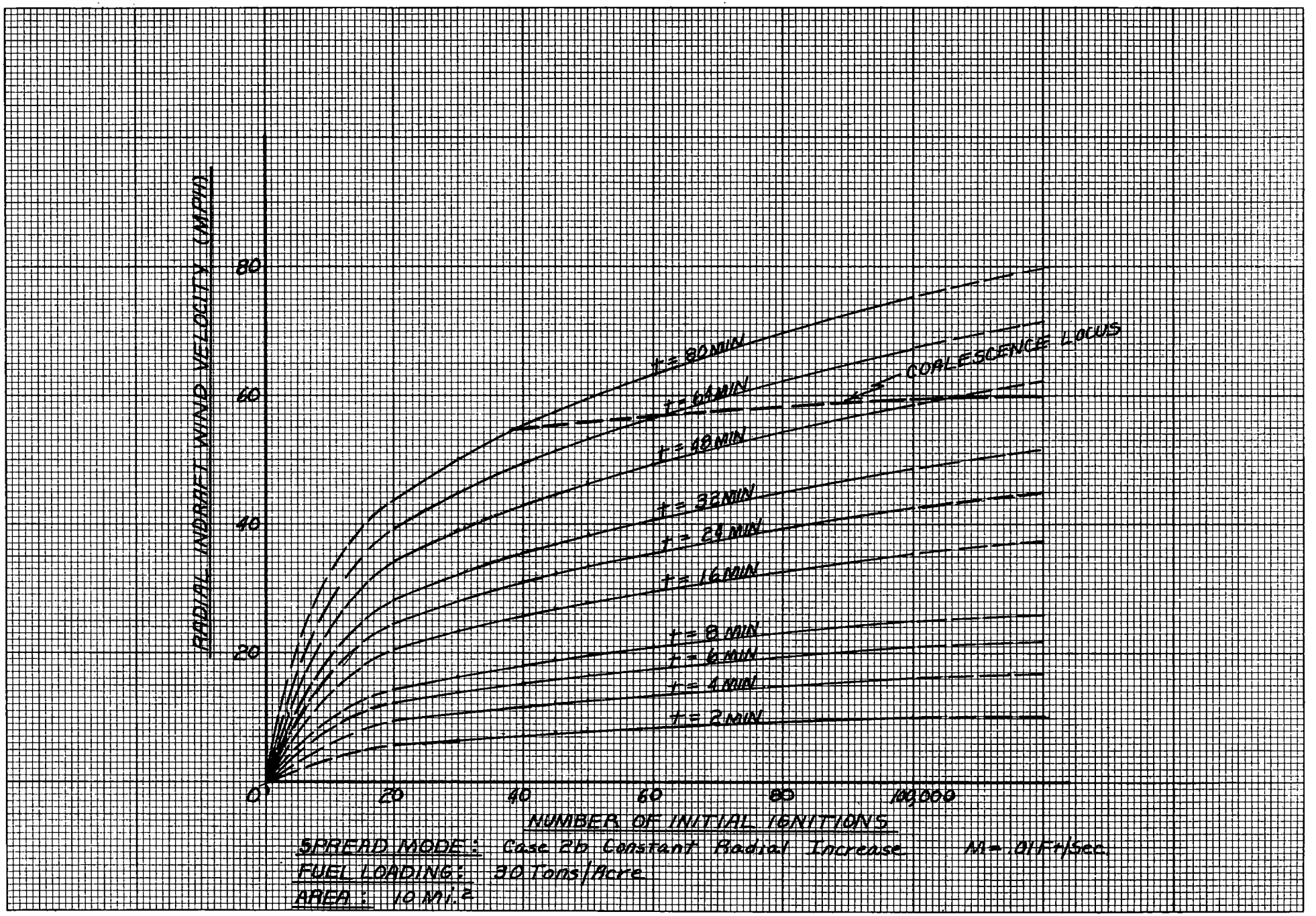

Fig. IV-43

FREDERICK POST COMPANY
301TR20 CROSS SECTION 20 X 20 PER INCH

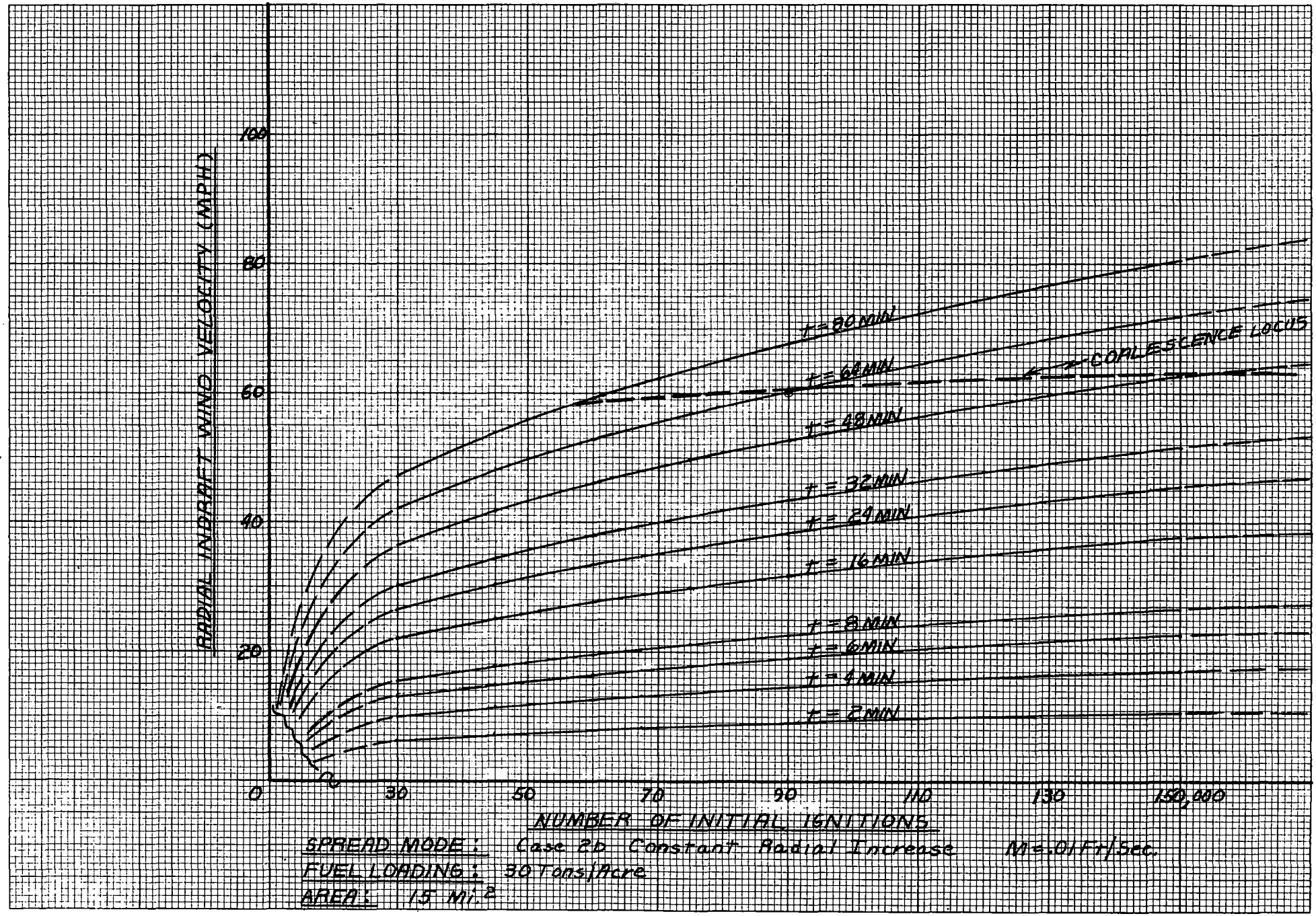

Fig. IV-44

FREDERICK POST COMPANY
301TR20 CROSS SECTION 20 X 20 PER INCH

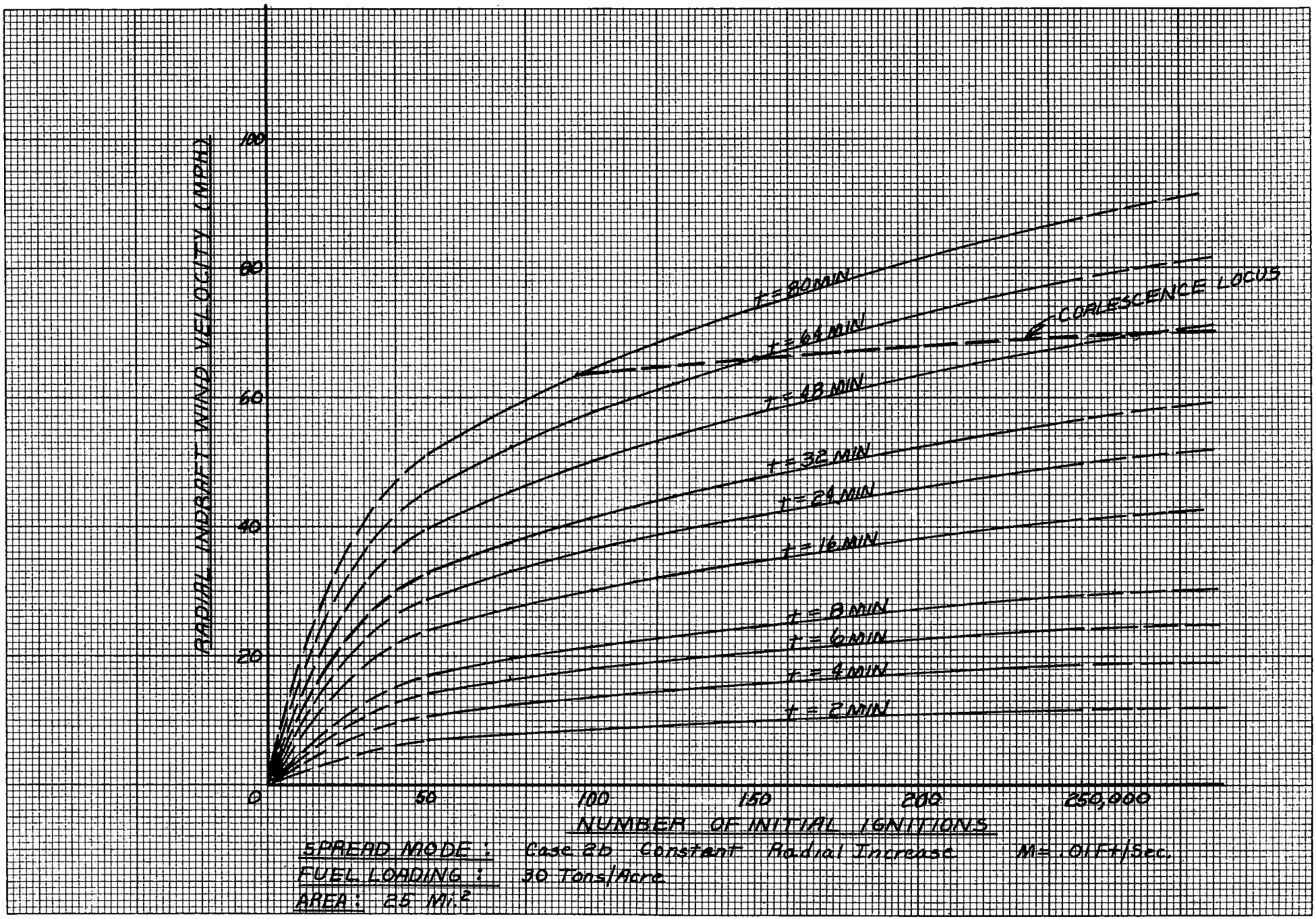

Fig. IV-45

APPENDIX V

SENSITIVITY CURVES

The following seven sets of curves are based upon the rationale and parameter values discussed in Appendix II and are drawn from the output of Part II of the computer program listed in Appendix III.

Each family of curves represents $\frac{\partial v_w}{\partial \mu_i}$ as a function of μ_i for ten different times with the other parameters μ_j ($j \neq i$) held at their "representative value" as listed in Table II-I.

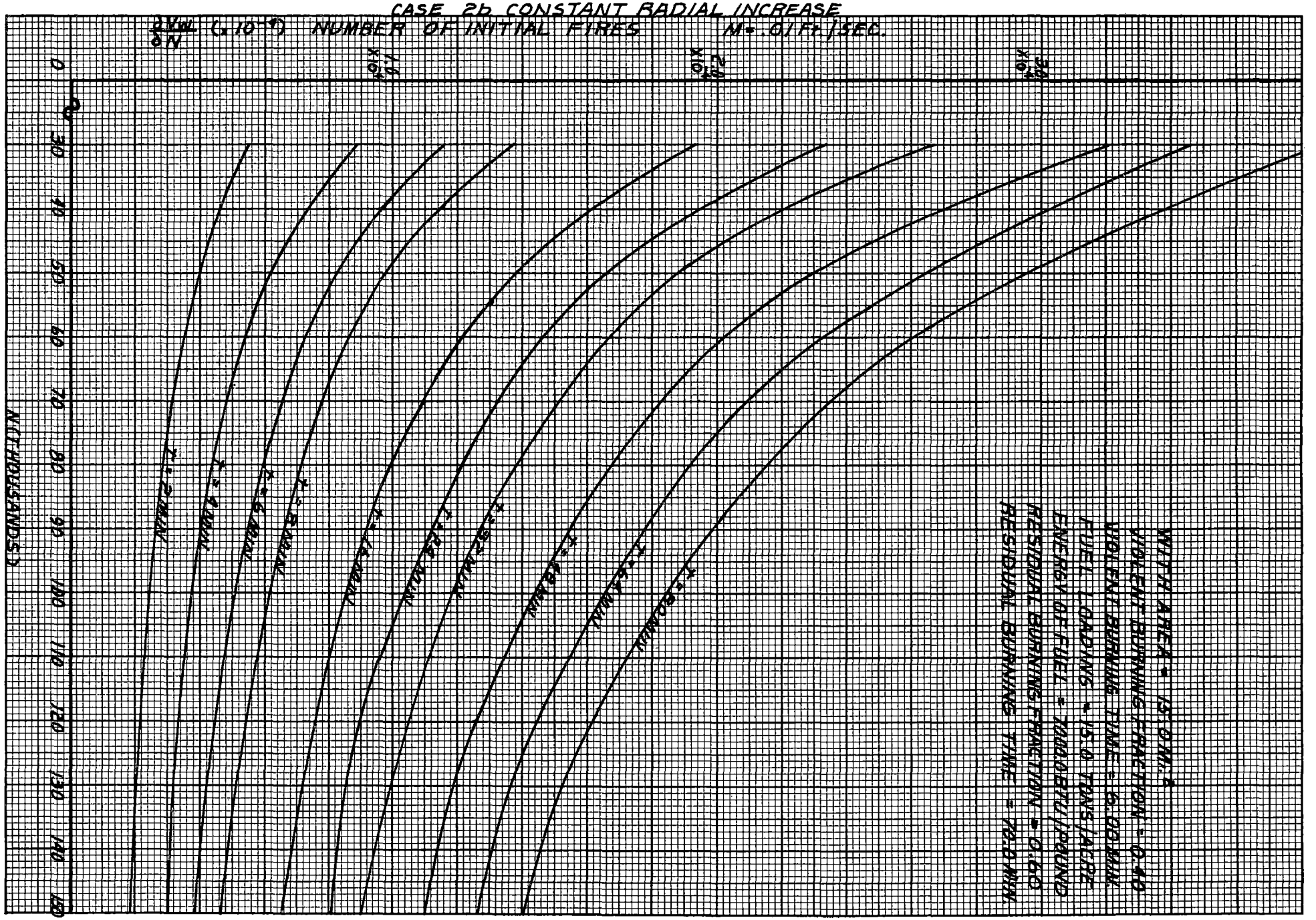
CASE 2b CONSTANT RADIAL INCREASE
NUMBER OF INITIAL FIRES
M = .6 MI./HR./SEC.
WITH AREA = 15.0 M.I.²
VIOLENT BURNING FRACTION = 0.40
VIOLENT BURNING TIME = 6.00 MIN.
FUEL LOADING = 15.0 TONS/ACRE
ENERGY OF FUEL = 7000 BTU/POUND
RESIDUAL BURNING FRACTION = 0.60
RESIDUAL BURNING TIME = 720.0 MIN
NUMBER OF THOUSANDS
0
30
40
50
60
70
80
90
100
110
120
130
140
150

Fig. V-1

KEUFFEL & ESSER CO.
MADE IN U.S.A.

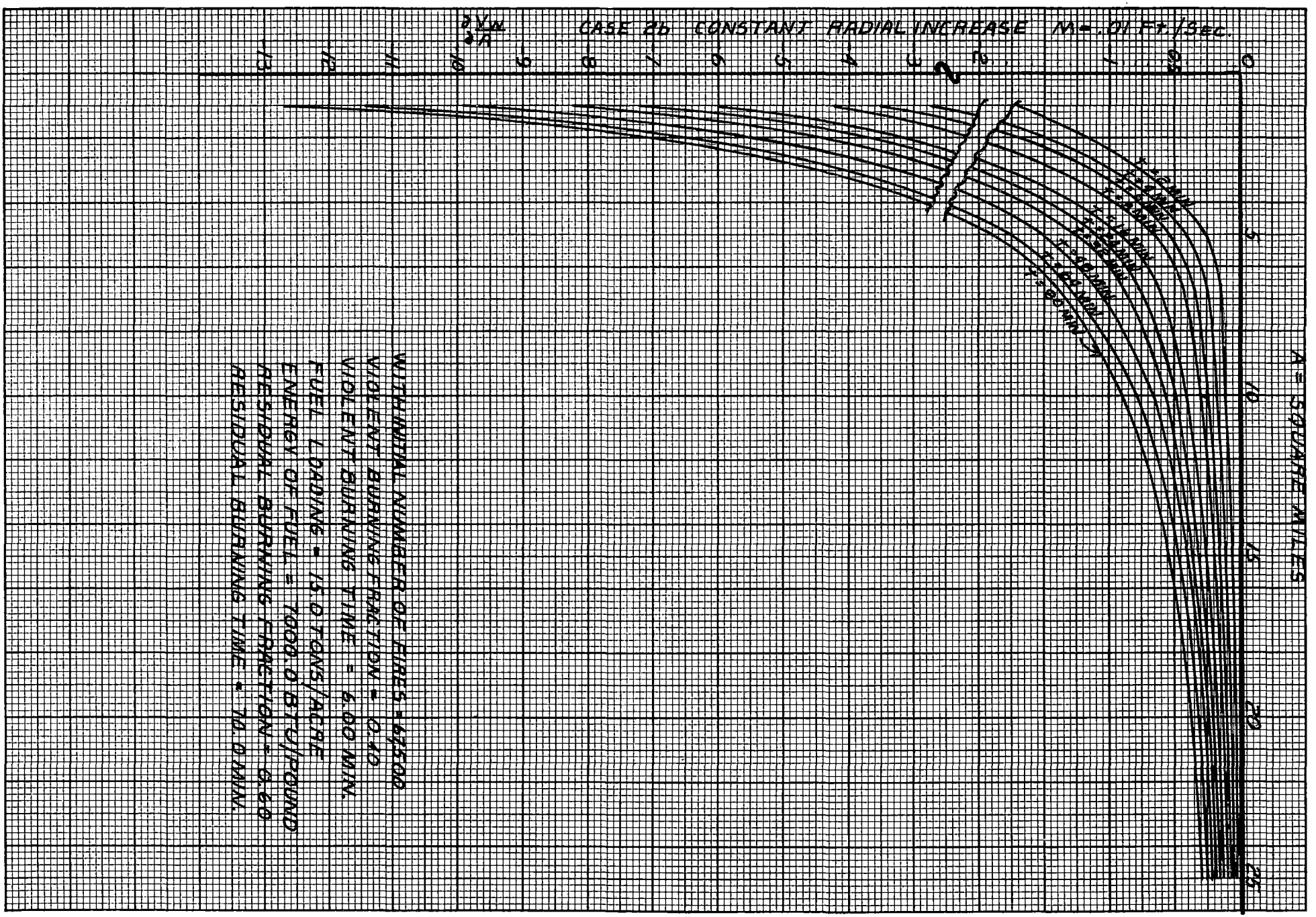
CASE 2b CONSTANT RADIAL INCREASE M = .01 Fr/3 sec.
$\frac{2V_M}{A}$
A = SQUARE MILES
WITH INITIAL NUMBER OF FIRES = 42500
VIOLENT BURNING FRACTION = 0.10
VIOLENT BURNING TIME = 6.00 MIN.
FUEL LOADING = 15.0 TONS/ACRE
ENERGY OF FUEL = 7600.0 BTU/POUND
RESIDUAL BURNING FRACTION = 0.60
RESIDUAL BURNING TIME = 70.0 MIN.

Fig. V-2

K&E 7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.

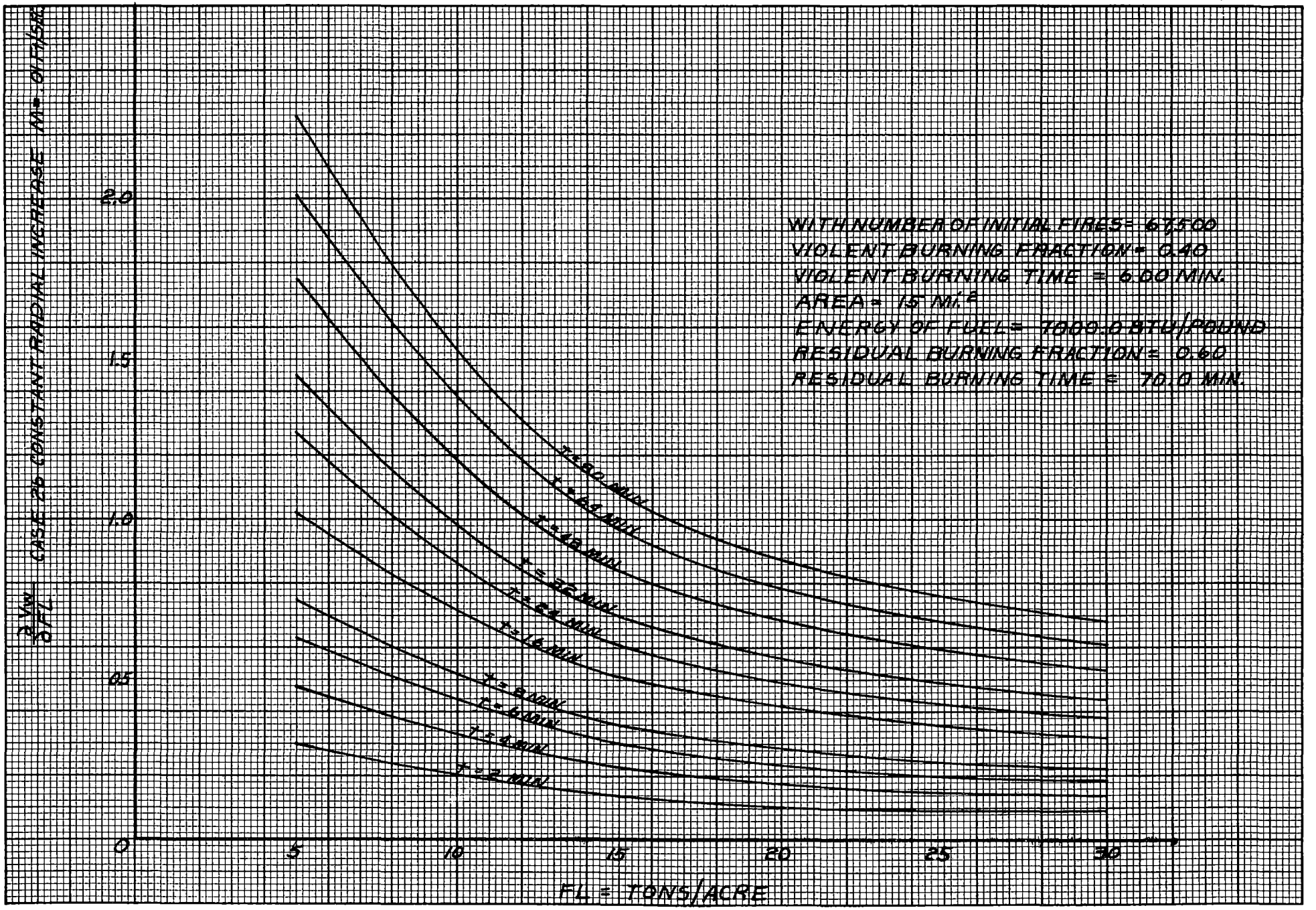

Fig. V-3

KEUFFEL & ESSER CO. MADE IN U.S.A. 7 X 10 INCHES 323

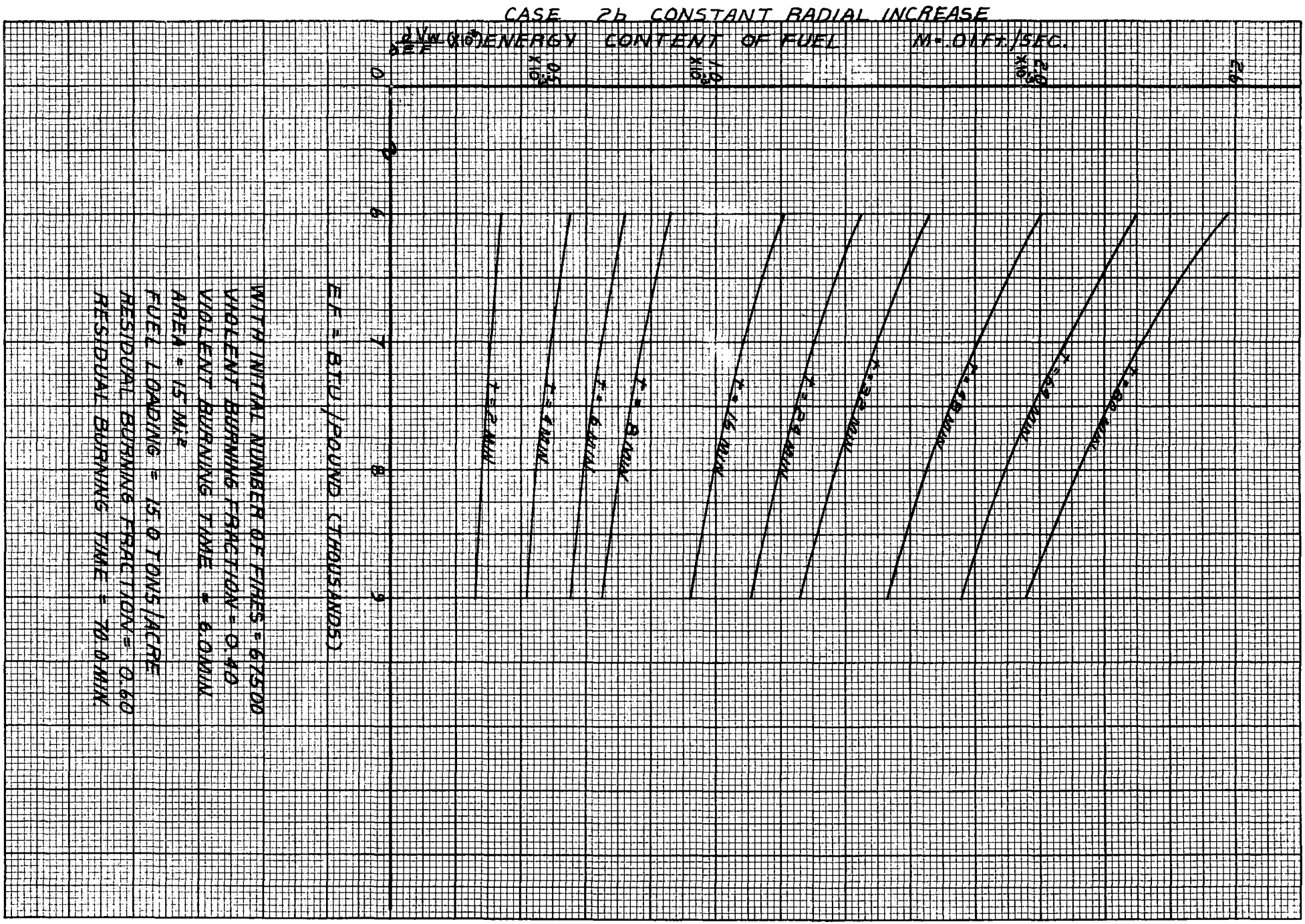

Fig. V-4

KEUFFEL & ESSER CO.

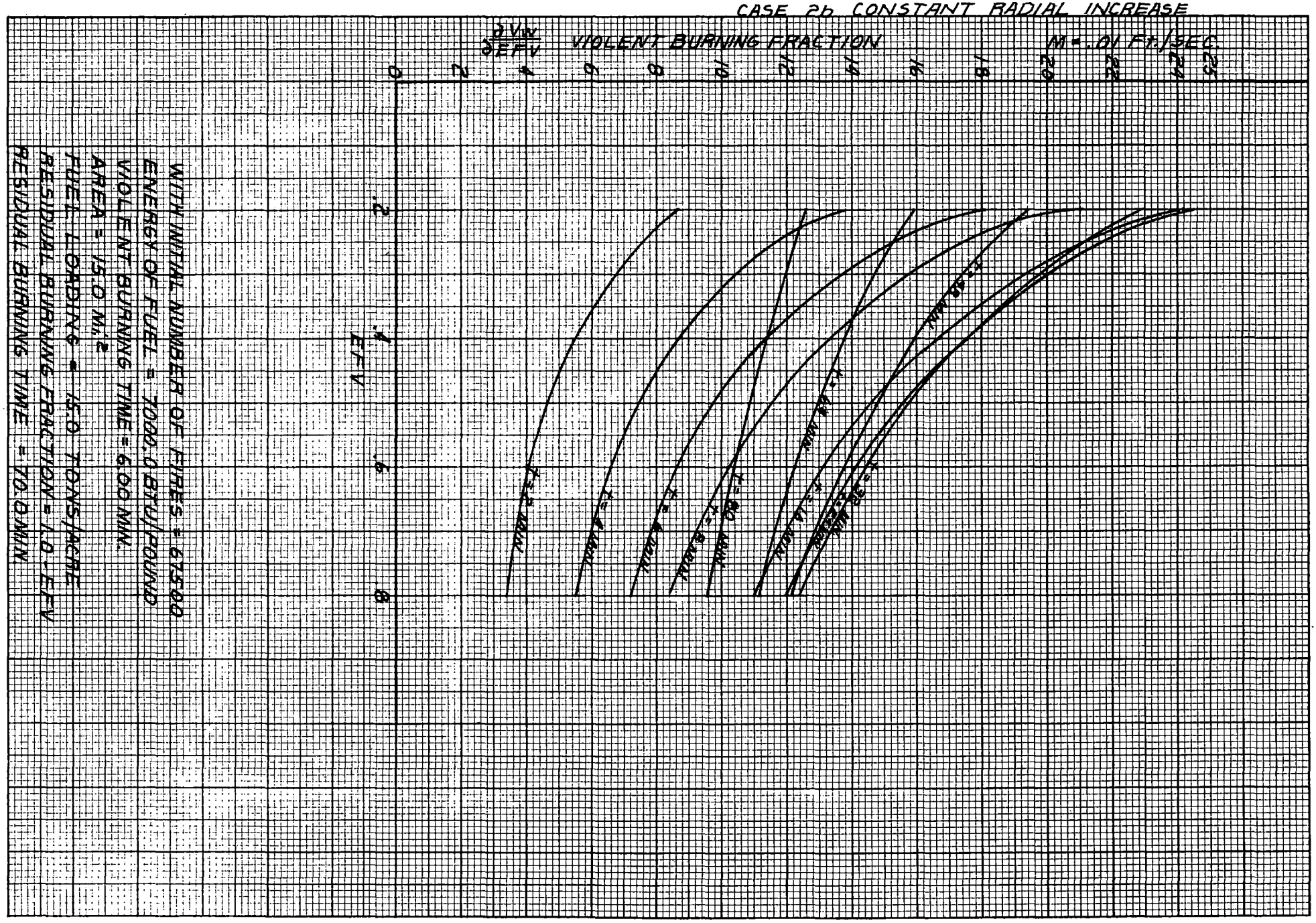

Fig. V-5

K+E 10 A 10 TO INCH .323
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.

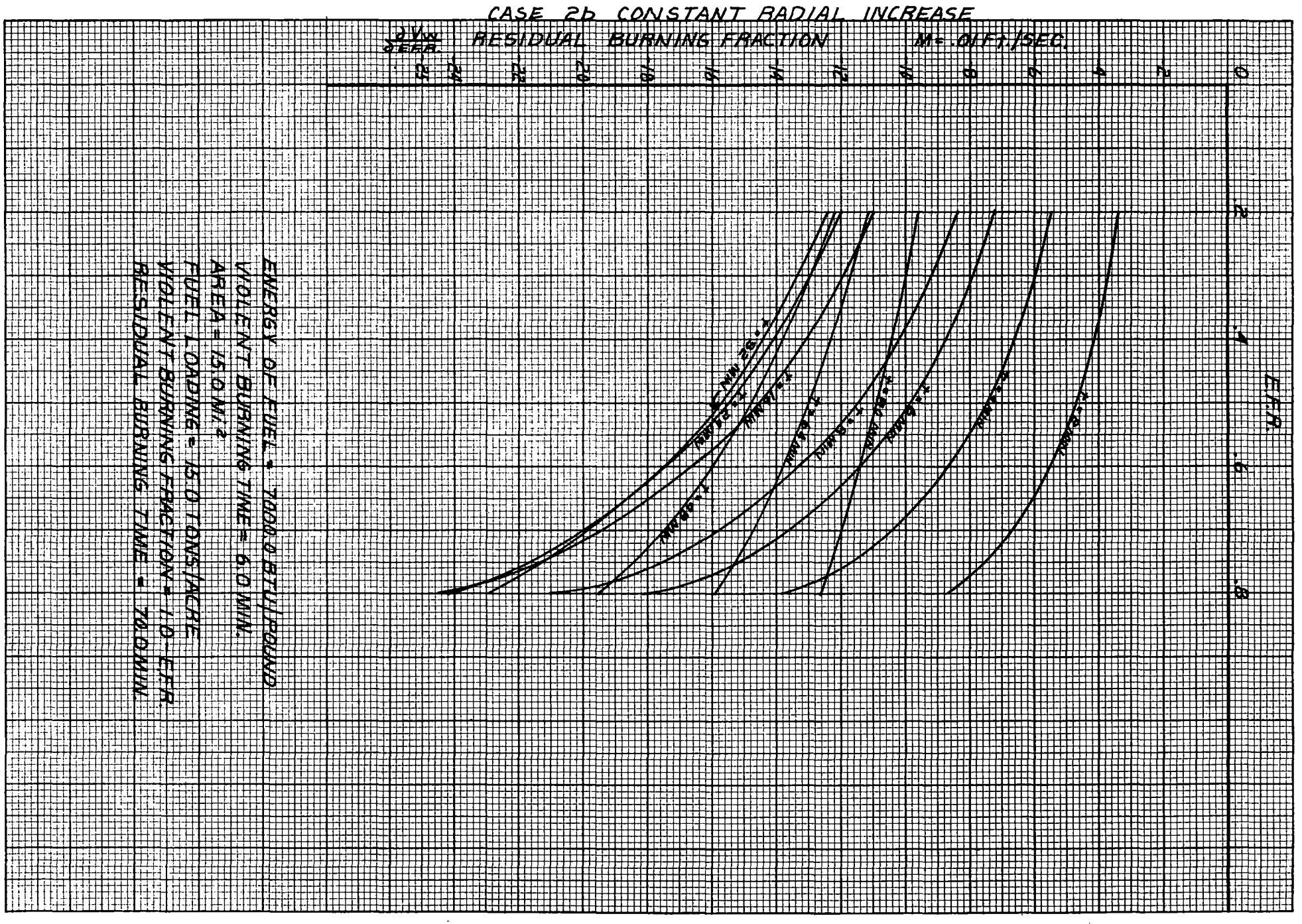
CASE 2b CONSTANT RADIAL INCREASE
RESIDUAL BURNING FRACTION
M= .01 Ft./SEC.
2Vw/3EFR.
2 1.8 1.6 1.4 1.2 1.0 .8 .6 .4 .2 0
EFR.
.2 .4 .6 .8 1.0
ENERGY OF FUEL = 7000.0 BTU/POUND
VIOLENT BURNING TIME = 6.0 MIN.
AREA = 15.0 MI.²
FUEL LOADING = 15.0 TONS/ACRE
VIOLENT BURNING FRACTION = 1.0 - EFR
RESIDUAL BURNING TIME = 70.0 MIN.

Fig. V-6

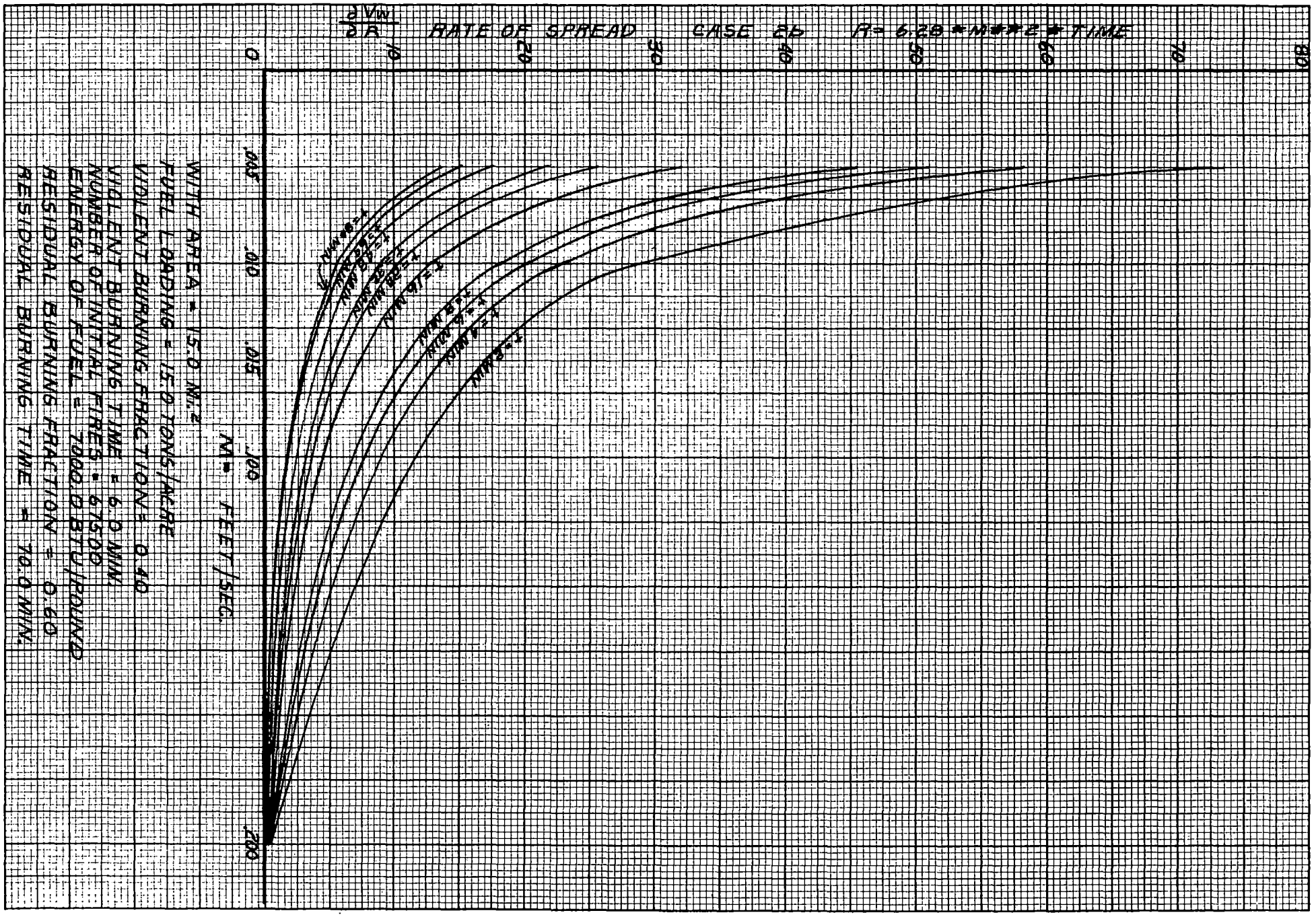
RATE OF SPREAD CASE 2b R= 6.28 * M**2 * TIME
0
10
20
30
40
50
60
70
80
.200
.100
.05
.010
.005
M= FEET/SEC.
WITH AREA = 15.0 MI.²
FUEL LOADING = 15.0 TONS/ACRE
VIOLENT BURNING FRACTION = 0.40
VIOLENT BURNING TIME = 6.0 MIN.
NUMBER OF INITIAL FIRES = 67500
ENERGY OF FUEL = 7000.0 BTU/POUND
RESIDUAL BURNING FRACTION = 0.60
RESIDUAL BURNING TIME = 70.0 MIN.

Fig. V-7

APPENDIX VI

ACCELERATED SPREAD STUDY

VI.1 General

Given n initial point fires distributed uniformly in an area A such that the initial separation distances between any fire and its nearest neighbors are equal, then D, x, and r_c are defined in Fig. VI-1 for any two fires.

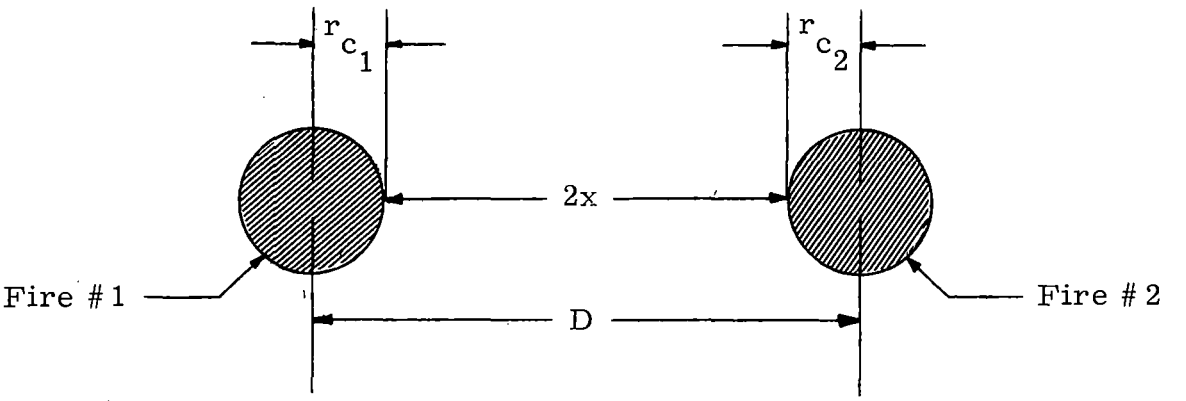

Fig. VI-1

Assume that $r_{c_1} = r_{c_2} = \phi(t)$, that both fires maintain essentially circular fronts as the fires spread, and the radius at any time t is r_c for each fire.

Let M represent the rate of radial spread in ft/min, so that

$$M = \frac{dr_c}{dt} \quad . \tag{VI. 1}$$

M, x, and r_c are to be determined as functions of time for four initial spread modes, with accelerated spread beginning at some value of r_c.

VI. 2 Accelerated Spread Relations*

Assume that for $r_c \geq [\sqrt{A/4n} - 3F]$, i.e., when $t > t_a$, spread is accelerated according to the hyperbolic relation

$$Mx = 3F \cdot M_a \quad , \tag{VI. 2}$$

where

A	is the fire area (sq ft),
n	is the total number of fires in area A,
F	is the flame height (assume F = 3 ft),
t_a	is the time at which accelerated spread begins,
x	is the distance of one fire front from the point of merging,
2x	is the minimum separation between fires (ft), and
M_a	is the value of M at t_a, which is the start of the accelerated spread, i.e., r_c at $t_a = \sqrt{A/4n} - 3F$.

NOTE: $D = \sqrt{A/n}$; therefore, since $x = \frac{1}{2}D - r_c$,

$$x \text{ at } t_a = 3F = 9 \text{ ft} \quad .$$

VI. 3 Initial Spread Mode One

For initial spread mode one, take, for $0 \leq r_c \leq [\sqrt{A/4n} - 3F]$,

---

* Provided by Mr. Craig C. Chandler, Division of Fire Research, U. S. Forest Service, Washington, D. C.

$$\left.\begin{aligned} M &= 0 \quad \text{if} \quad t \leq 1/6760 \text{ min} \\ M &= \frac{1.27}{2\pi} \log_{10}(6760\,t) \quad \text{for} \quad \frac{1}{6760} < t \leq t_a \end{aligned}\right\} . \qquad \text{(VI. 3)}^*$$

Then, since

$$r_c(t) = \int_0^t M dt = \frac{1.27}{2\pi} \int_{\frac{1}{6760}}^t \log_{10}(6760\,t)\, dt \quad , \qquad \text{(VI. 4)}$$

$$r_c(t) = \frac{1.27}{2\pi(\ln 10)} \left[t[\ln(6760\,t) - 1] + \frac{1}{6760} \right] \quad , \qquad \text{(VI. 5)}$$

and

$$x(t) = \tfrac{1}{2} D - r_c(t) = \tfrac{1}{2} \sqrt{A/n} - r_c(t) \quad , \qquad \text{(VI. 6)}$$

where $r_c(t)$ is the value of r_c at time t.

VI. 4 Initial Spread Mode Two

For initial spread mode two, take, for $0 \leq r_c \leq [\sqrt{A/4n} - 3F]$,

$$\left.\begin{aligned} M &= 0 \quad \text{if} \quad t \leq 1/0.91 \text{ min} \\ M &= \frac{6.67}{2\pi} \log_{10}(0.91\,t) \quad \text{for} \quad \frac{1}{0.91} < t \leq t_a \end{aligned}\right\} . \qquad \text{(VI. 7)}^*$$

As before, integration of Eq. (VI. 7) yields

---

* Provided by Mr. Craig C. Chandler, Division of Fire Research, U. S. Forest Service, Washington, D. C.

$$r_c(t) = \frac{6.67}{2\pi(\ln 10)} \left[t\left[\ln(0.91\,t) - 1\right] + \frac{1}{0.91} \right] \quad ; \qquad \text{(VI. 8)}$$

and, also

$$x(t) = \tfrac{1}{2} D - r_c(t) = \tfrac{1}{2}\sqrt{A/n} - r_c(t) \quad . \qquad \text{(VI. 9)}$$

VI. 5 Initial Spread Mode Three

Consider now the case of constant rate of radial increase for $t \leq t_a$, with

$$M = 0.01 \text{ ft/sec} = 0.6 \text{ ft/min} \quad . \qquad \text{(VI. 10)}$$

In this case,

$$r_c(t) = 0.6\,t \quad , \qquad \text{(VI. 11)}$$

and, as before

$$x(t) = \tfrac{1}{2} D - r_c(t) \quad . \qquad \text{(VI. 12)}$$

VI. 6 Initial Spread Mode Four

Also, consider the case of constant rate of area increase up to $t = t_a$, i. e.,

$$\frac{dA}{dt} = K_1 = 5 \text{ ft}^2/\text{sec} = 300 \text{ ft}^2/\text{min} \quad . \qquad \text{(VI. 13)}$$

Now

$$\frac{dA}{dt} = \frac{d(\pi r_c^2)}{dt} = 2\pi r_c \frac{dr_c}{dt} = 2\pi r_c M \quad , \qquad \text{(VI. 14)}$$

and equating (VI. 13) with (VI. 14) yields

$$2\pi r_c M = 300 \text{ ft}^2/\text{min} \quad . \qquad \text{(VI. 15)}$$

Taking Eq. (VI. 15) and remembering that

$$M = \frac{dr_c}{dt} = r_c' \quad ,$$

we have that

$$r_c r_c' = \frac{300}{2\pi} = C \qquad \text{(VI. 16)}$$

with the initial condition that $r_c(0) = 0$.

Hence,

$$r_c(t) = \sqrt{2Ct} = \sqrt{\frac{300\,t}{\pi}} \quad , \qquad \text{(VI. 17)}$$

and, as before

$$x(t) = \tfrac{1}{2}D - r_c(t) \quad . \qquad \text{(VI. 18)}$$

Also, differentiation of Eq. (VI. 17) yields

$$M = \sqrt{\frac{75}{\pi t}} \quad . \qquad \text{(VI. 19)}$$

VI. 7 Method of Calculation

A computer program has been written based upon the foregoing which calculates M, r_c, and x as functions of time for $0 \leq r_c < \frac{1}{2}D$. A listing of this program and its input requirements is included in Appendix VII.

VI. 8 Results

The results of calculations with the above program are presented graphically in Appendix VIII.

APPENDIX VII

ACCELERATED SPREAD PROGRAM

VII. 1 General

The following program is based upon the accelerated spread rationale explained in Appendix VI, and calculates spread rate (M), fire radius (r_c), and distance to merging (x) for each of the four initial spread modes discussed in Appendix VI, with acceleration for each mode beginning when $x \leq 3F$, where F represents the flame height. The program is written in FORTRAN IV for an IBM System/360 Model 40G digital computer. The program is in three parts. The first part performs the calculations for each initial spread mode. SUBROUTINE PRINT prints the results of these calculations up to the point of acceleration, and SUBROUTINE ACC performs the calculations and prints the results for each initial mode after acceleration begins.

VII. 2 Data Cards

The first card has format I12 and contains NSETS, the number of data sets to be used in the run.

Each data set consists of a single card with format 5E12. 4 containing the following inputs:

Column	Program Symbol	Units	Variable
1-12	D	feet	Initial separation between fires
13-24	F	feet	Flame height
25-36	TINC	minutes	Time increment of calculation for initial spread
37-48	TM1	minutes	Spread start time for Mode 1
49-60	TM2	minutes	Spread start time for Mode 2

NOTE: Due to the form of the equations for initial spread modes one and two, TM1 must be greater than 1/6760 minutes and TM2 must be greater than 1/0.91 minutes.

VII. 3 Program Listing

(See following pages.)

```
C       PROGRAM SPREAD
        DIMENSION T(1500),M(1500),RC(1500),X(1500)
        REAL M,MA
        PI=3.14159
        READ (1,1) NSETS
1       FORMAT (I12)
C       NSETS IS THE NUMBER OF DATA SETS
        DO 21 K=1,NSETS
        READ (1,2) D,F,TINC,TM1,TM2
C       D IS THE INITIAL SEPARATION BETWEEN FIRES IN FEET
C       F IS THE FLAME HEIGHT IN FEET
C       TINC IS THE TIME INCREMENT IN MINUTES FOR INITIAL SPREAD
C       TM1 IS THE SPREAD START TIME FOR MODE ONE
C       TM2 IS THE SPREAD START TIME FOR MODE TWO
C       RC IS THE FIRE RADIUS IN FEET
C       X IS THE DISTANCE TO MERGING IN FEET
C       M IS THE RATE OF RADIAL SPREAD IN FEET PER MINUTE
C       T IS TIME IN MINUTES
2       FORMAT (5E12.4)
        MODE=0
        T(1)=TINC
C       THIS LOOP CALCULATES SPREAD FOR MODE ONE
        TEST=3.0*F
        DO 7 I=1,1000
        IF (T(I)-TM1) 3,3,4
3       M(I)=0
        RC(I)=0
        GO TO 5
4       M(I)=1.27/(2.0*PI)*ALOG10(6760.0*T(I))
        RC(I)=1.27/(2.0*PI*ALOG(10.0))*(T(I)*(ALOG(6760.0*T(I))-1.0)
       $+1.0/6760.0)
5       X(I)=0.5*D-RC(I)
        II=I
        IF (X(I)-TEST) 8,8,6
6       T(I+1)=(I+1)*TINC
7       CONTINUE
8       MA=M(II)
        TA=T(II)
        XA=X(II)
        RA=RC(II)
        MODE=MODE+1
        CALL PRINT (X,M,T,RC,II,MODE,D,F)
        CALL ACC (XA,MA,TA,RA,X,M,T,RC,MODE,F)
        GO TO (9,15,18,21),MODE
9       T(1)=TINC
C       THIS LOOP CALCULATES SPREAD FOR MODE TWO
        DO 14 I=1,1000
        IF (T(I)-TM2) 10,10,11
10      M(I)=0.0
        RC(I)=0.0
        GO TO 12
11      M(I)=6.67/(2.0*PI)*ALOG10(0.91*T(I))
```

```
      RC(I)=6.67/(ALOG(10.0)*2.0*PI)*(T(I)*(ALOG(0.91*T(I))-1.0)
     $+1.0/0.91)
12    X(I)=0.5*D-RC(I)
      II=I
      IF (X(I)-TEST) 8,8,13
13    T(I+1)=(I+1)*TINC
14    CONTINUE
15    T(1)=TINC
C     THIS LOOP IS FOR SPREAD MODE THREE, CONSTANT RADIAL INCREASE
      DO 17 I=1,1000
      M(I)=0.6
      RC(I)=0.6*T(I)
      X(I)=0.5*D-RC(I)
      II=I
      IF (X(I)-TEST) 8,8,16
16    T(I+1)=(I+1)*TINC
17    CONTINUE
18    T(1)=TINC
C     THIS LOOP CALCULATES SPREAD FOR MODE FOUR
      DO 20 I=1,1000
      M(I)=SQRT(75.0/(PI*T(I)))
      RC(I)=SQRT((300.0*T(I))/PI)
      X(I)=0.5*D-RC(I)
      II=I
      IF (X(I)-TEST) 8,8,19
19    T(I+1)=(I+1)*TINC
20    CONTINUE
21    CONTINUE
      RETURN
      END
      SUBROUTINE PRINT (X,M,T,RC,II,MODE,D,F)
      DIMENSION X(1),M(1),T(1),RC(1)
1     FORMAT (1H1,10X,19HINITIAL SEPARATION=,F12.4,10X,13HFLAME HEIGHT=
     $,F12.4,10X,21HSPREAD MODE IS NUMBER,I5)
      NPG=II/96
      L=II-NPG*96
      M1=1
      M2=96
      DO 4 K=1,NPG
      WRITE (3,1) D,F,MODE
      WRITE (3,2)
2     FORMAT (1HO,1X,2(12X,4HTIME,5X,11HSPREAD RATE,5X,11HFIRE RADIUS
     $,3X,14HMERGE DISTANCE))
      WRITE (3,3) (T(J),M(J),RC(J),X(J),J=M1,M2)
3     FORMAT (2X,8F16.4)
      M1=M1+96
      M2=M2+96
4     CONTINUE
      IF (L) 9,9,5
5     IF (NPG) 6,6,7
6     M1=1
      M2=L
```

```
      GO TO 8                                                          105
7.    M2=M1+L-1                                                        106
8     WRITE (3,1) D,F,MODE                                             107
      WRITE (3,2)                                                      108
      WRITE (3,3) (T(J),M(J),RC(J),X(J),J=M1,M2)                       109
9     RETURN                                                           110
      END                                                              111
      SUBROUTINE ACC (XA,MA,TA,RA,X,M,T,RC,MODE,F)                     112
C     THIS SUBROUTINE CALCULATES SPREAD RATE, RADIUS, AND              113
C     SEPARATION DISTANCE AFTER ACCELERATION BEGINS                    114
      DIMENSION X(1),T(1),M(1),RC(1)                                   115
      REAL M,MA                                                        116
      DT=.005                                                          117
      X(1)=XA                                                          118
      M(1)=MA                                                          119
      T(1)=TA                                                          120
      RC(1)=RA                                                         121
      DO 1 J=2,1500                                                    122
      X(J)=X(J-1)-M(J-1)*DT                                            123
      M(J)=3.0*F*MA/X(J)                                               124
      RC(J)=RA+XA-X(J)                                                 125
      T(J)=TA+DT*(J-1)                                                 126
      IF (X(J)-.05) 2,2,1                                              127
1     CONTINUE                                                         128
2     LPINC=4                                                          129
      N=J-LPINC+1                                                      130
      LPPG=96*LPINC                                                    131
      NPG=N/LPPG                                                       132
      L=N-NPG*LPPG                                                     133
      M1=1                                                             134
      M2=LPPG                                                          135
      DO 3 KK=1,NPG                                                    136
      WRITE (3,8) MODE                                                 137
      WRITE (3,9)                                                      138
      WRITE (3,10) (T(K),M(K),RC(K),X(K),K=M1,M2,LPINC)                139
      M1=M1+LPPG                                                       140
      M2=M2+LPPG                                                       141
3     CONTINUE                                                         142
      IF (L) 11,11,4                                                   143
4     IF (NPG) 5,5,6                                                   144
5     M1=1                                                             145
      M2=L                                                             146
      GO TO 7                                                          147
6     M2=M1+L-1                                                        148
7     WRITE (3,8) MODE                                                 149
      WRITE (3,9)                                                      150
      WRITE (3,10) (T(K),M(K),RC(K),X(K),K=M1,M2,LPINC)                151
8     FORMAT (1H1,40X,'ACCELERATION PHASE FOR INITIAL SPREAD MODE',I5)  152
9     FORMAT (1H0,1X,2(12X,4HTIME,5X,11HSPREAD RATE,5X,11HFIRE RADIUS  153
     $,3X,14HMERGE DISTANCE))                                          154
10    FORMAT (2X,8F16.4)                                               155
11    RETURN                                                           156
```

APPENDIX VIII

ACCELERATED SPREAD CURVES

The following eight curves show spread rate (M) as a function of time (t) and fire radius (r_c) for each of the four initial spread modes discussed in Appendix VI, with the point at which accelerated spread begins indicated by the symbol ▲ beside each curve.

These curves are drawn from the output of the computer program described in Appendix VII, with an initial separation between fires (D) of 78.8 feet, a flame height (F) of 3.0 feet, TINC = 0.1 minutes, TM1 = .000148 minutes, and TM2 = 1.1 minutes.

The value of D was taken from the formula $D = \sqrt{A/n}$, with $n = A \cdot n_d$. Using the representative values of A and n_d as discussed in Appendix II,

$$D = \sqrt{\frac{15.0\,(5280)^2}{15.0 \cdot 4500}} = \frac{528}{3}\sqrt{1/5} = 78.8 \text{ ft} \quad .$$

K+E 10 X 10 TO 7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.

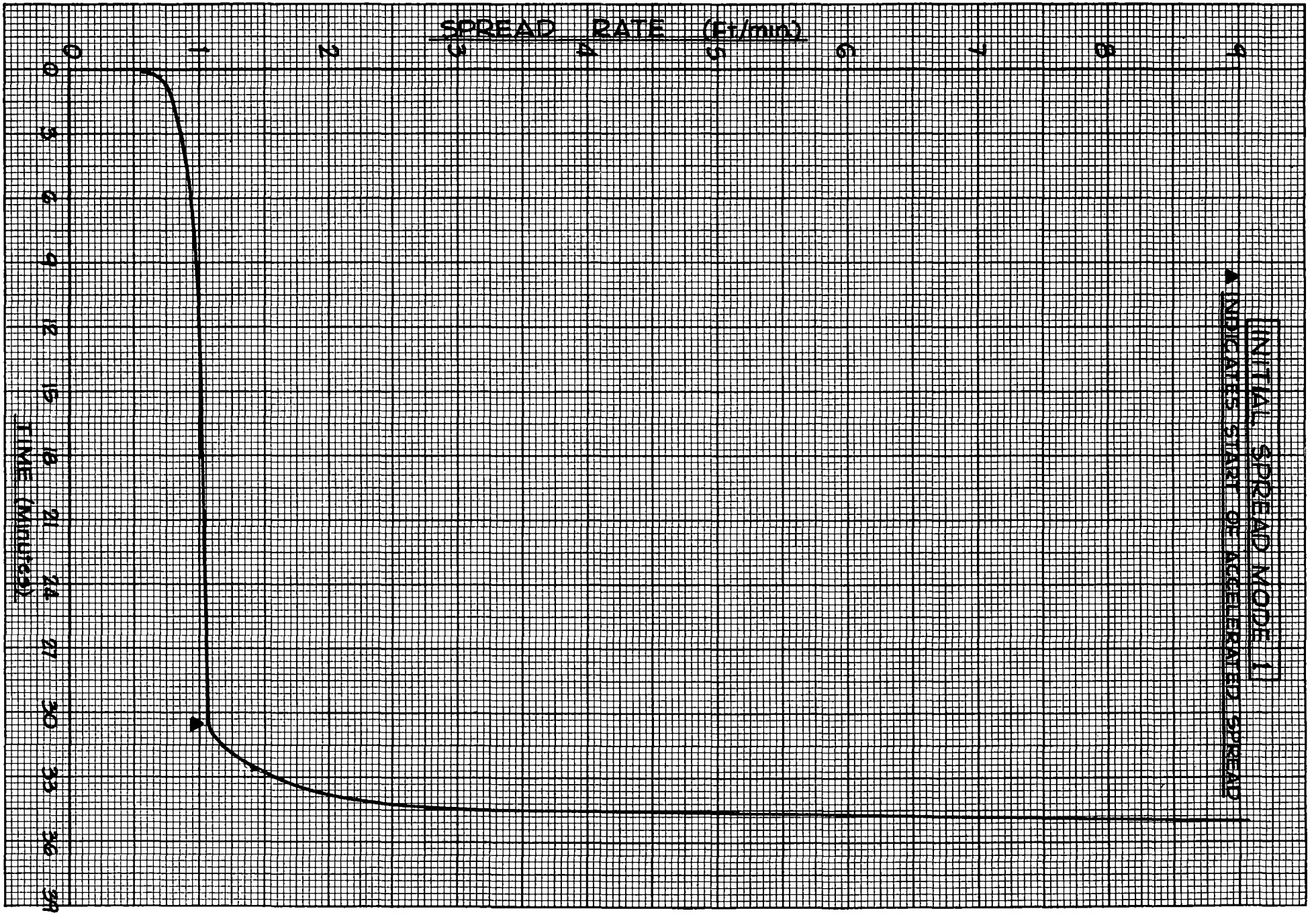

Fig. VIII-1

2046.

K+E 10 X 10 TO ½ INCH 323
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.

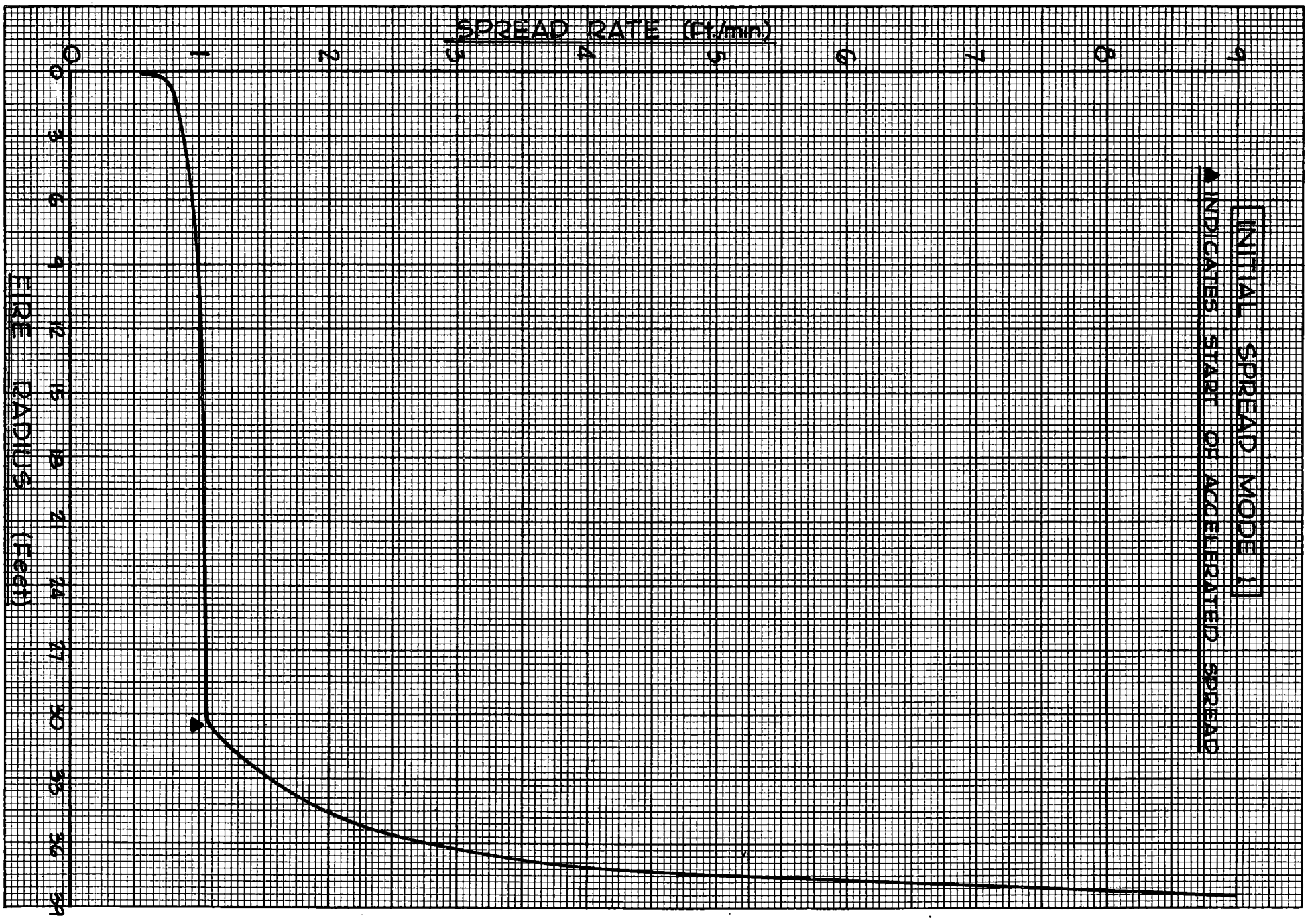

Fig. VIII-2

K&E 10 X 10 TO 1 CM 46 1023
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.

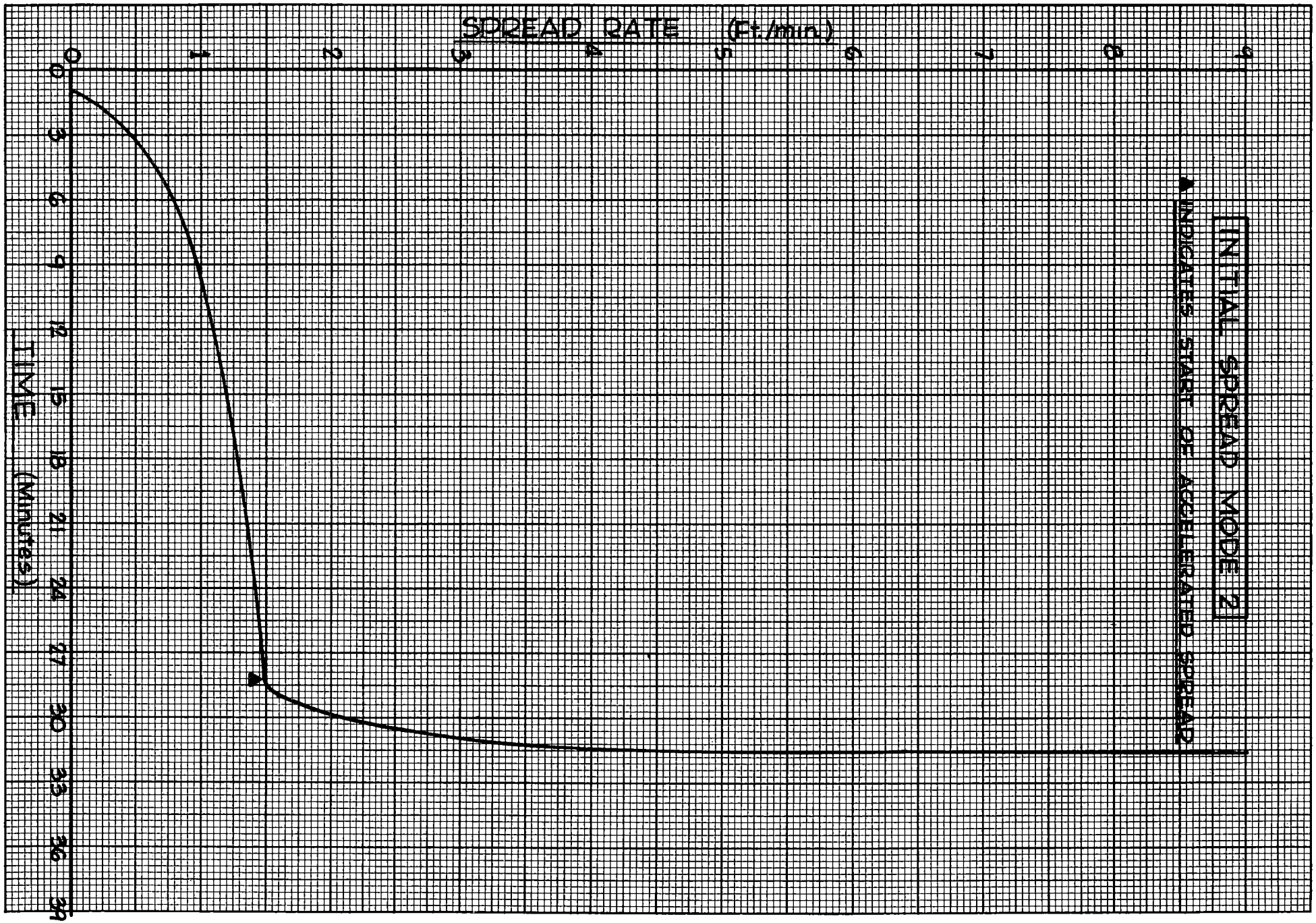

Fig. VIII-3

K+E 10 X 10 TO ½ INCH 46 1323
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.

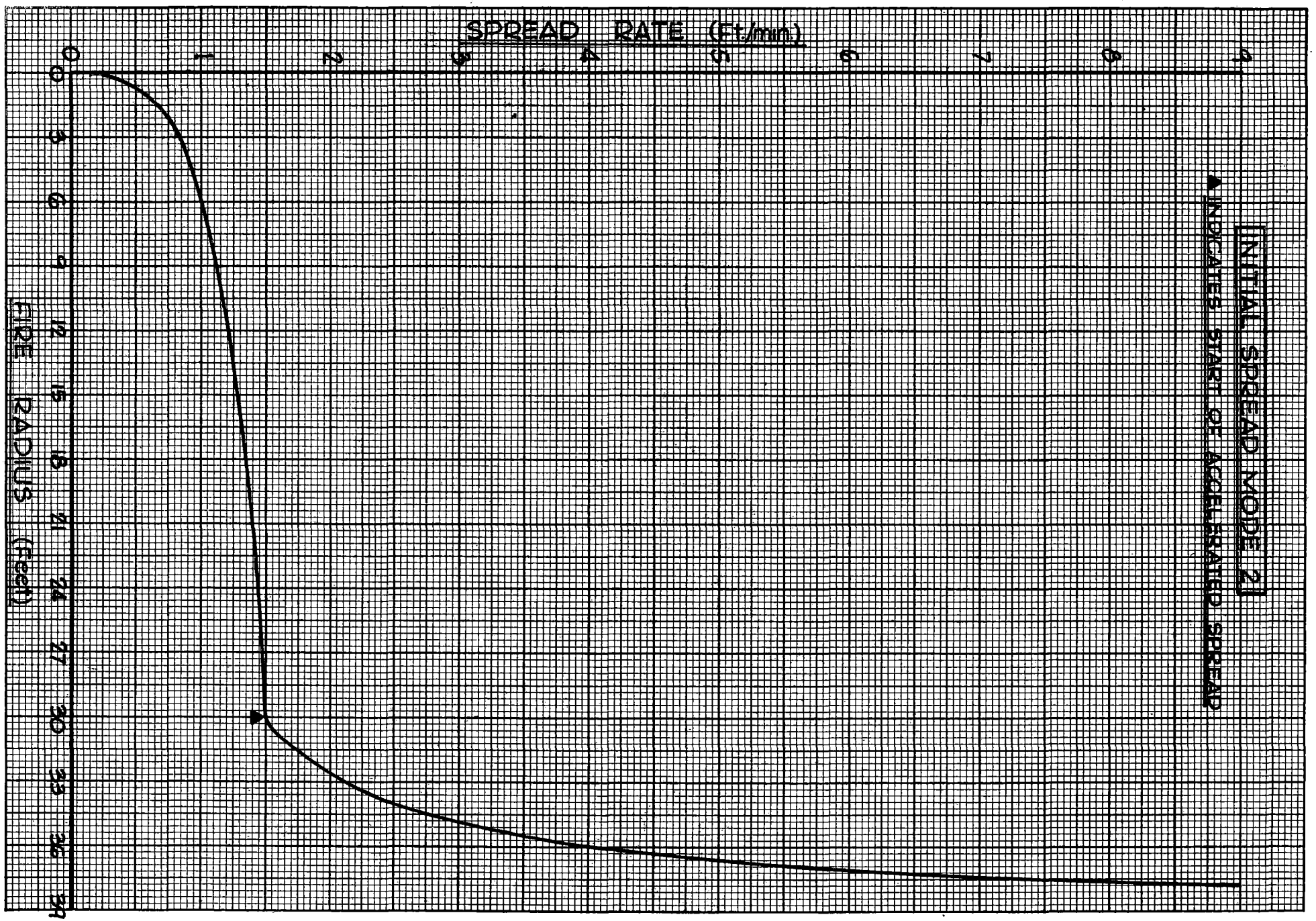

Fig. VIII-4

KEUFFEL & ESSER CO.
MADE IN U.S.A.
7 X 10 INCHES

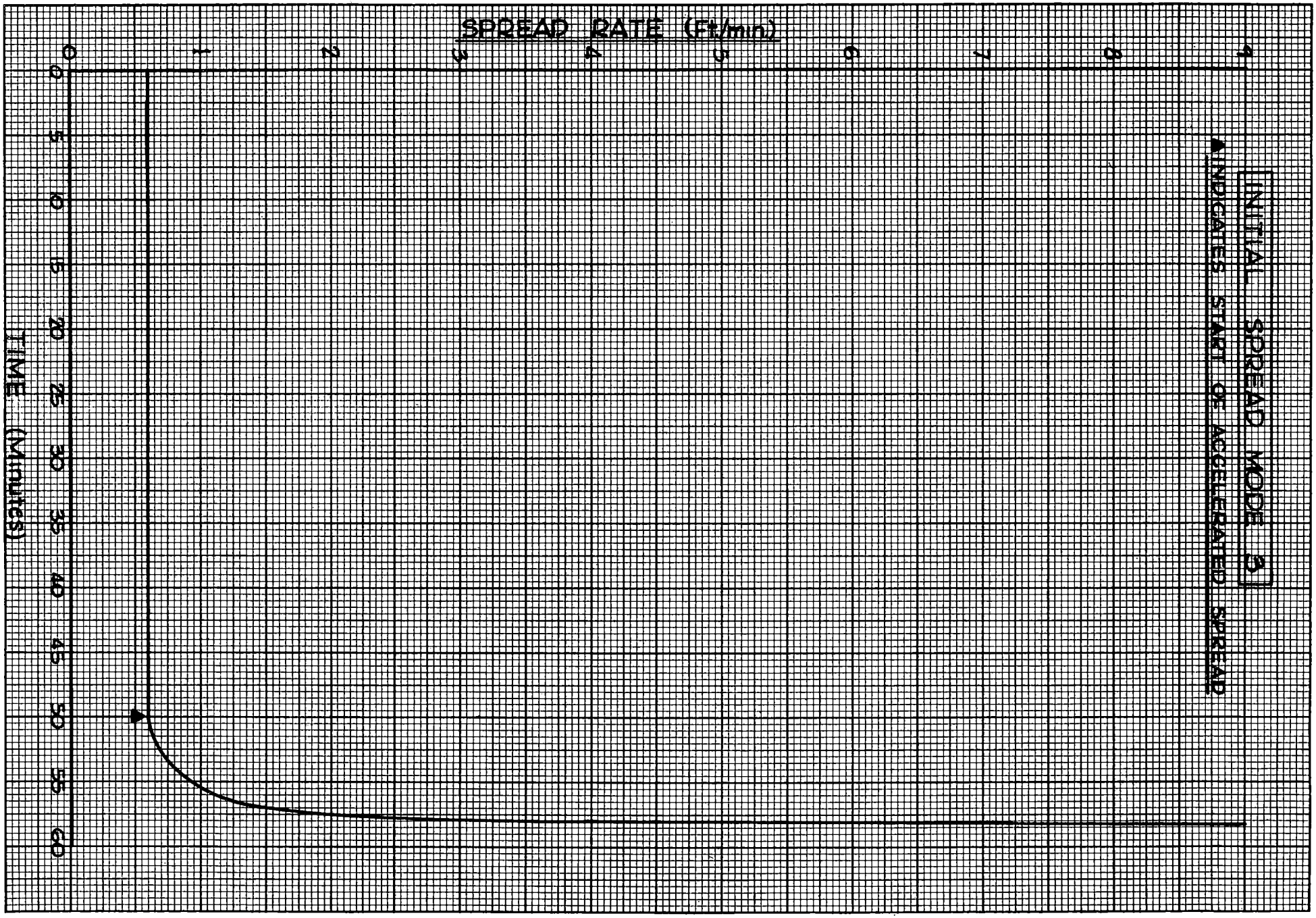

Fig. VIII-5

KEUFFEL & ESSER CO.

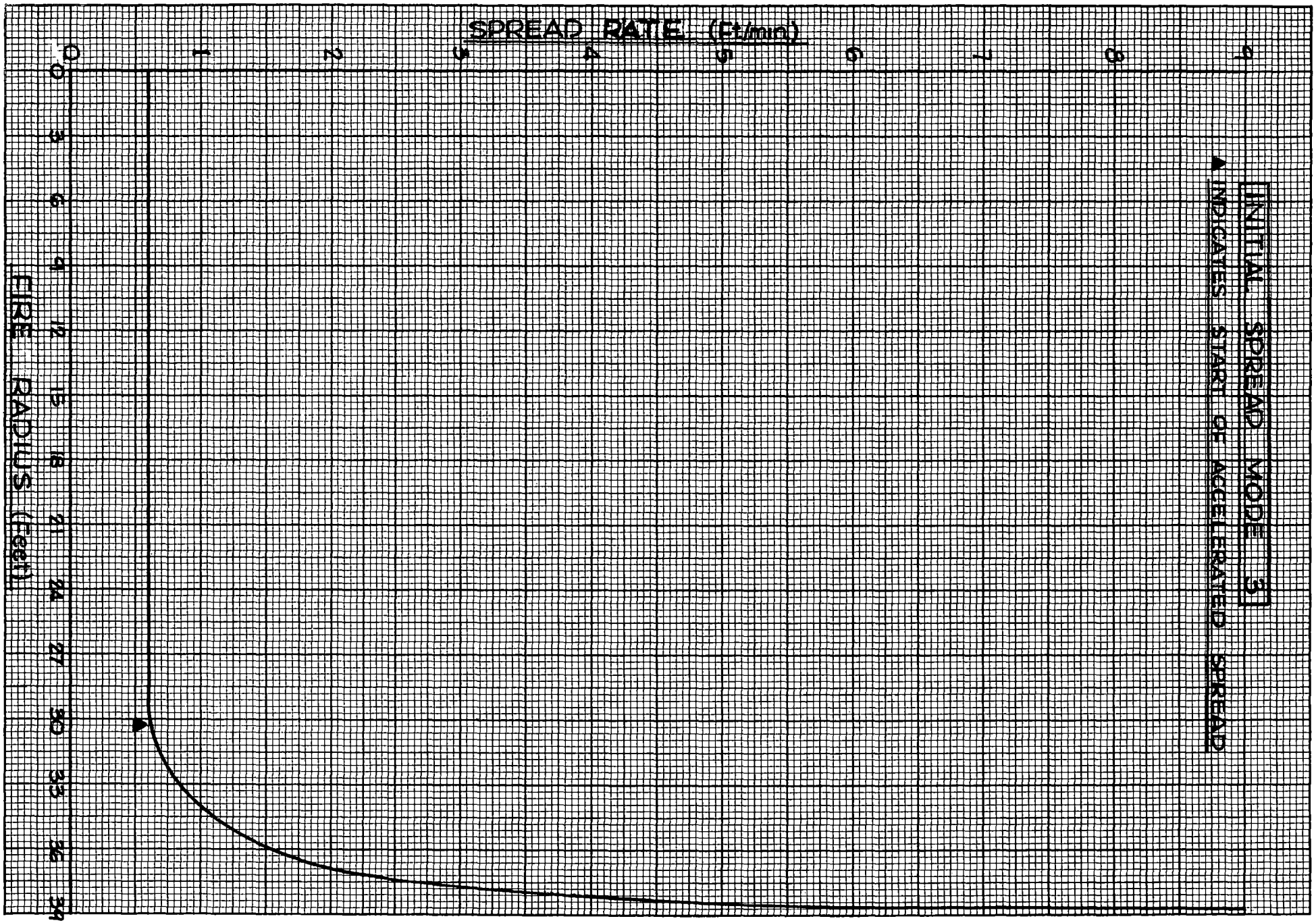

Fig. VIII-6

KEUFFEL & ESSER CO.

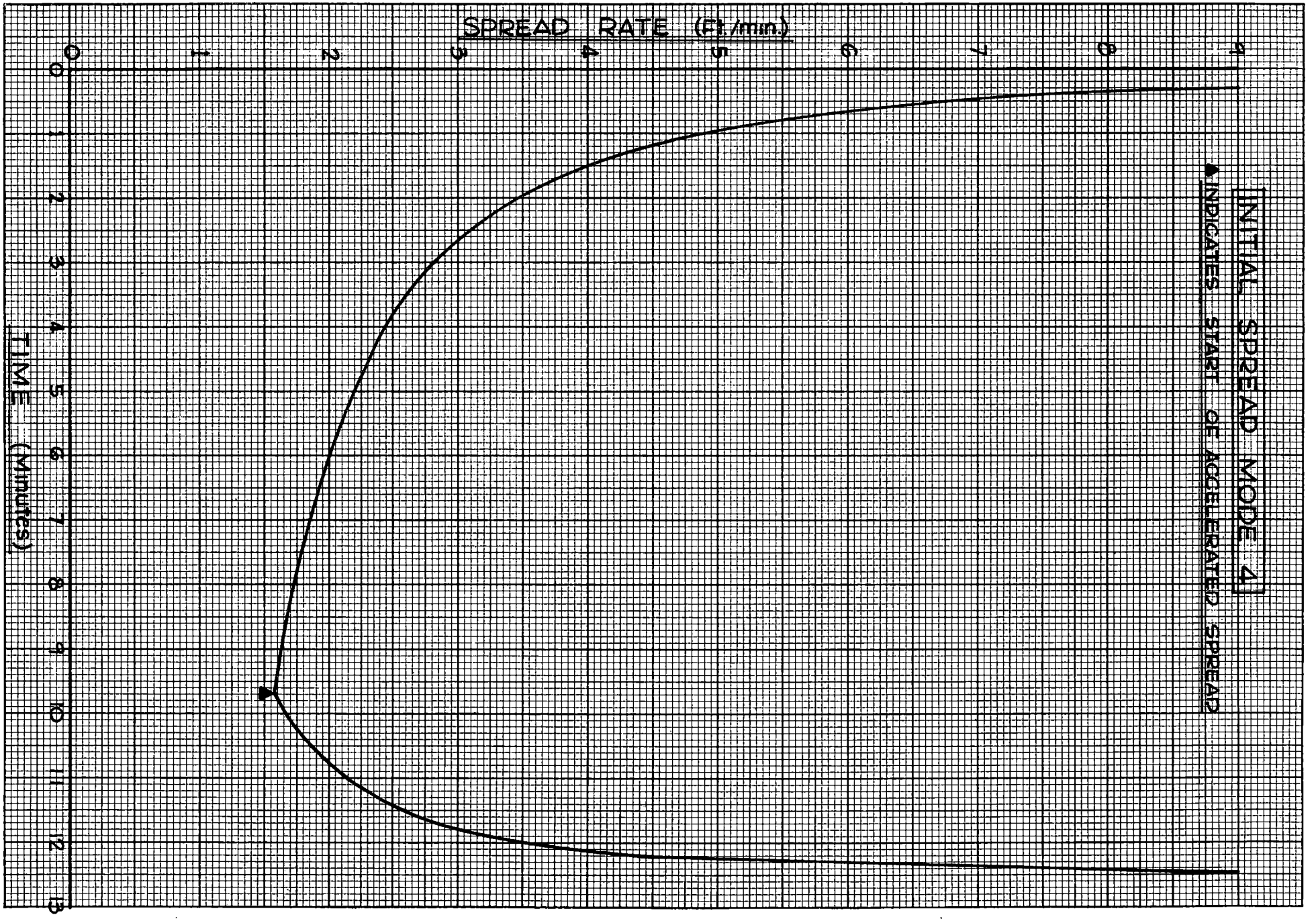

Fig. VIII-7

KEUFFEL & ESSER CO.

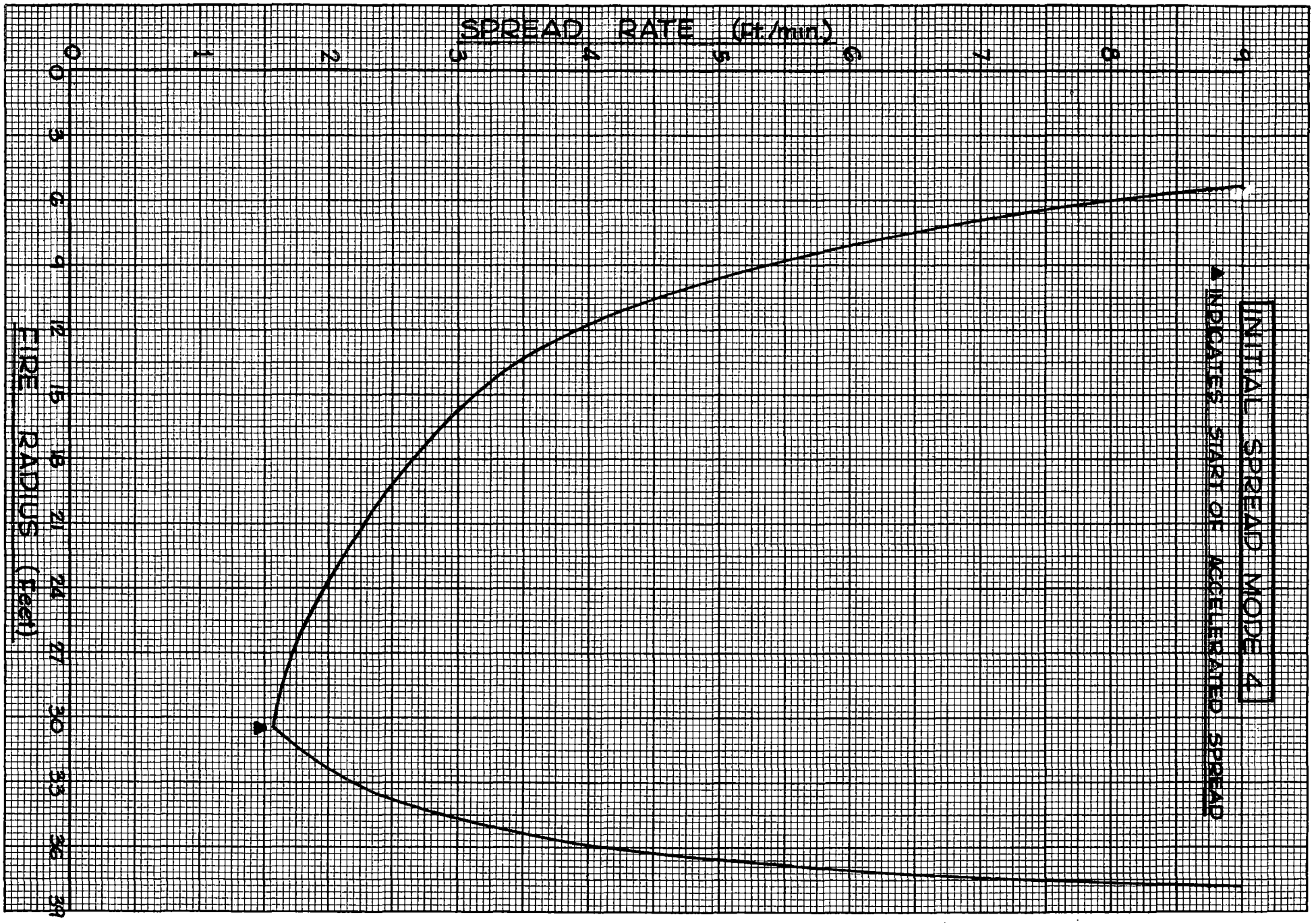

Fig. VIII-8